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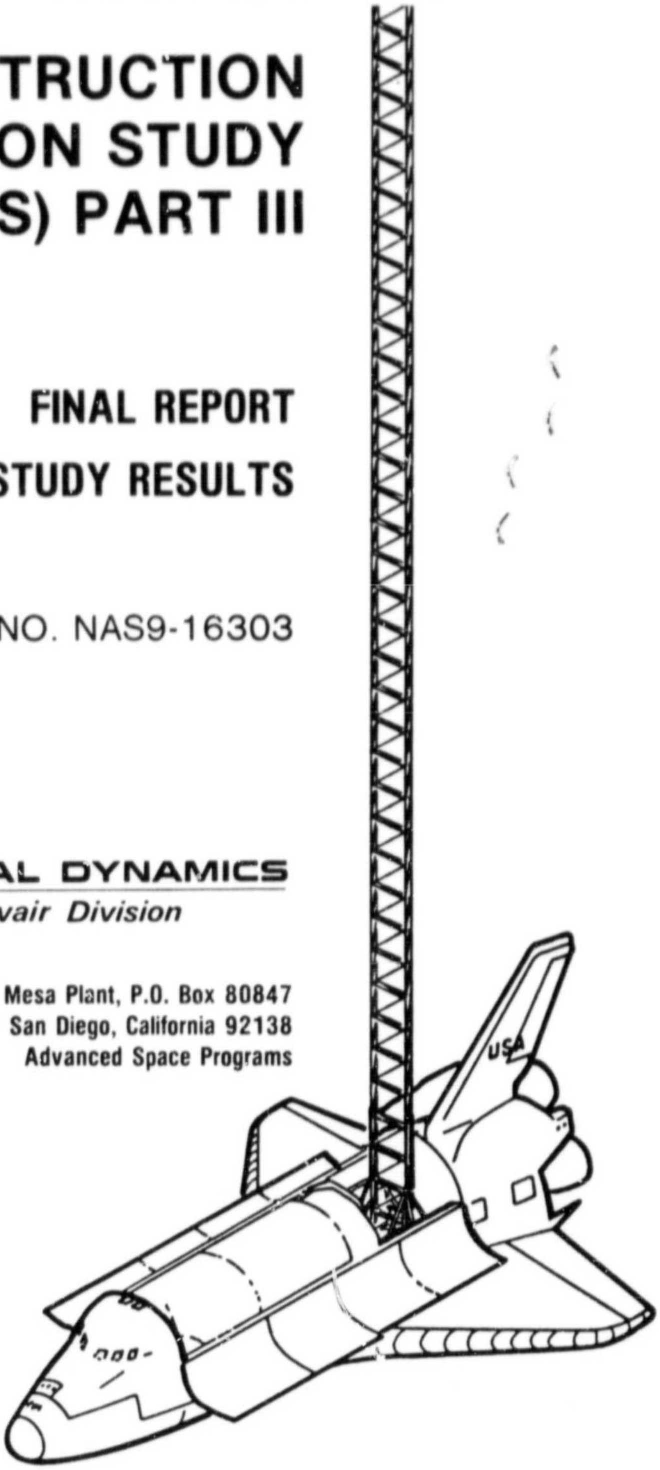
SPACE CONSTRUCTION EXPERIMENT DEFINITION STUDY (SCEDS) PART III

FINAL REPORT

VOLUME II • STUDY RESULTS

CONTRACT NO. NAS9-16303



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SPACE CONSTRUCTION EXPERIMENT DEFINITION STUDY (SCEDS) PART III

FINAL REPORT

VOLUME II • STUDY RESULTS

March 1983

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FOREWORD

The final report was prepared by General Dynamics Convair Division for NASA/JSC in accordance with Contract NAS9-1603, DRL No. T-346, DRD No. MA-664T, Line Item No. 3. It consists of two volumes: (I) a brief Executive Summary and (II) a comprehensive set of Study Results.

General Dynamics Convair personnel who significantly contributed to the Part III study include:

Study Manager	John Bodle, Andy Robertson
Control Dynamics	Ray Halstenberg, John Sesak
Preliminary Design	Chuck Lungerhausen
Avionics & Controls	Stan Maki
Structural Analysis	Debbie Hung
Structural Dynamics	Bob Benner, Bob Peller
Mass Properties	Dennis Stachowitz
Economic Analysis	Bob Bradley

The study was conducted in Convair's Advanced Space Programs Department, directed by D. E. Charhut. The NASA/JSC COR is Lyle Jenkins of the Program Development Office.

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SECTION 1

INTRODUCTION

1.1 SCOPE

This is the second of two volumes comprising the SCEDs Final Report. It contains the detailed results of all Part III study tasks. Volume I provides an executive summary of the study results. This report is the final deliverable contract data item.

1.2 STUDY OVERVIEW.

1.2.1 PART I SUMMARY. The Part I study tasks focused on the definition of a baseline Space Construction Experiment (SCE) concept, shown in Figure 1-1 and concepts for additional suitcase experiments for Extravehicular Activity (EVA) and Remote Multipulator System (RMS) construction operations.

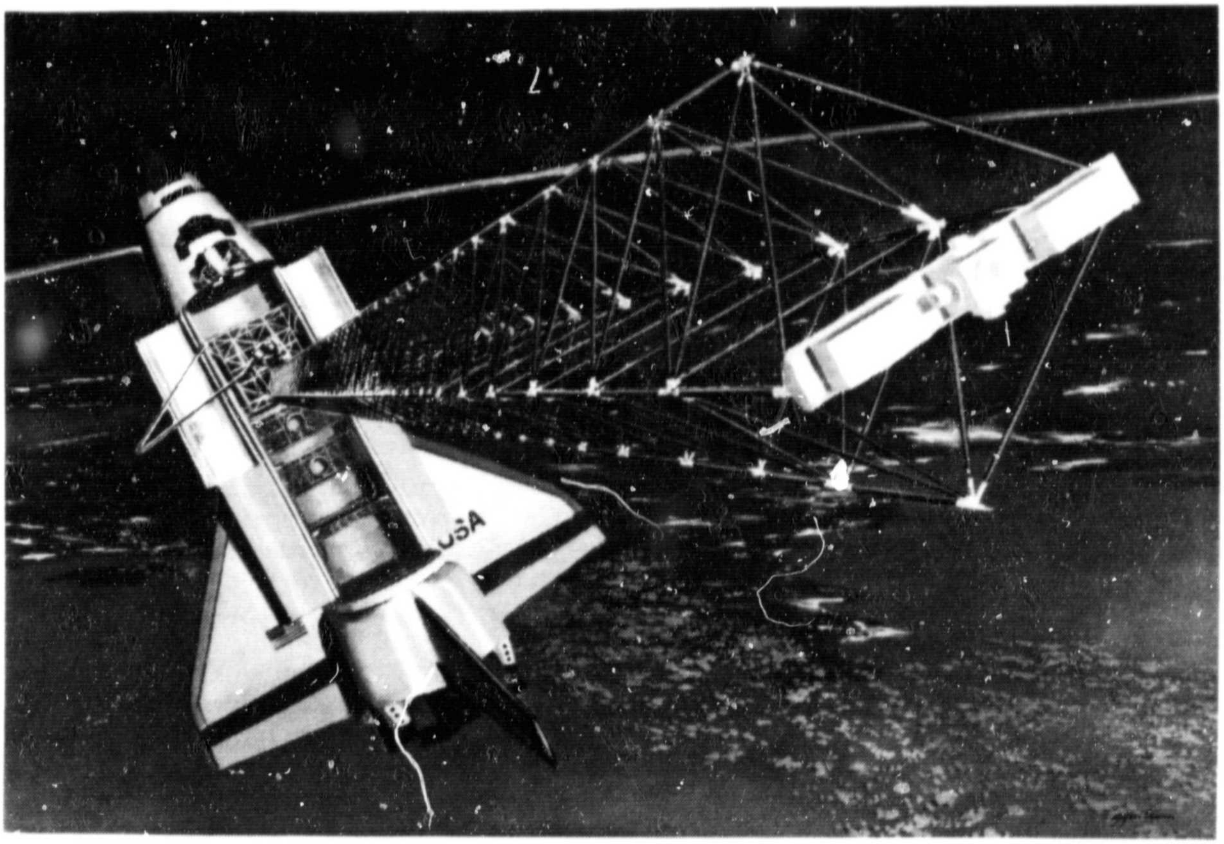

Figure 1-1. Baseline Flight Experiment Concept

The baseline structure is a tetrahedral diamond cross-section truss beam having a very low coefficient of thermal expansion, achievable through the use of graphite composite materials for construction. Structural dynamic tests will provide data to be correlated with math model predictions. Minimal ground testing is to be performed, and minimum flight instrumentation employed.

The experiment is to remain attached to the Orbiter throughout the test. Jettison capability is provided; however, the experiment will normally be automatically retracted, restowed, and returned to earth by the Orbiter.

A variety of appropriate Large Space System (LSS) construction and assembly operations utilizing basic Space Transportation System (STS) capabilities (EVA, RMS, CCTV, Illumination, etc.) were to be conducted and correlated with ground tests and simulations.

1.2.2 PART II SUMMARY. After the conclusion of Part I, the study objectives were expanded by NASA JSC and NASA LaRC to place greater emphasis on the structural dynamics and controls technology aspects of the experiments and to specifically design the experiment to develop and demonstrate the technologies to meet requirements for large space antenna feed masts. The objectives continued to stress the development of Orbiter capabilities necessary to support large space structures construction operations, including the ability to maneuver and control large attached structures and to perform in-space deployment and construction operations.

The Part II study activities were divided into the following major tasks. Further development and definition of the SCE for intergration into the Space Shuttle. This included development of flight assignment data, revision and update of preliminary mission timelines and test plans, analysis of flight safety issues, and definition of ground operations scenarios.

Convair also provided revised SCE structural dynamic characteristics to the Charles Stark Draper Laboratory for simulation and analysis of experimental tests to define and verify control limits and interactions effects between the SCE and the Orbiter Digital Automatic Pilot (DAP).

1.2.3 PART III SUMMARY. The part III study tasks were directed toward definition of an early shuttle controls and dynamics flight experiment, as well as evolutionary or supplemental experiments, that will address the needs of the dynamics and controls community and demonstrate the shuttle system capability

to perform construction operations. The requirement to experimentally evaluate shuttle digital Autopilot (DAP) interactions was dropped for Phase III. A new requirement that the first bending mode of the SCE be above 0.15 Hertz to avoid coupling with the DAP was adopted.

The level of definition of the first flight experiment is to be in sufficient detail required for NASA to prepare for competitive procurement. Also the planned availability of the NASA, LaRC developed Space Technology Experiments Platform (STEP) provided a resource that could be effectively utilized as part of the proposed experiment. Integration of the experiment with STEP was accomplished during the Phase III study.

The major objectives of Phase III were to:

- o Propose & define an extended controls & dynamics flight research program using the Part II test article
- o Propose & define enhanced test configurations for follow-on flight research
- o Establish needs for & benefits of flight research objectives
- o Integrate test article with the Space Technology Experiments platform (STEP)
- o Revise and update mission timelines, preliminary test plan and the preliminary program plan (including cost estimates and the schedule).

All objectives were satisfied and the results are presented in detail in the subsequent sections of this report.

SECTION 2

EXPERIMENT OBJECTIVES ANALYSIS

In order to establish an experiment series which is responsive to the needs of the technical community, an analysis of possible experiment objectives was conducted. Two complementary approaches were used to evaluate objectives for the flight experiment. First, technology needs were identified and ranked from a project manager's standpoint. As a separate effort, research areas were identified on the level of interest of the individual discipline engineer. For example, the discipline engineer would be concerned about the relative detailed characteristics of various control theories whereas the manager would want assurance that at least one suitable theory was available.

The technology needs were given preliminary rankings and reviewed by personnel from NASA, JPL, and Draper Lab. A final technology needs ranking was then established. Following this, the needs were compared with the research areas to provide assurance that no significant objective was overlooked. Based on the ranked objectives, a first flight experiment sequence was designed. This analysis approach is presented diagrammatically in Figure 2-1. In addition, the potential of comparatively simple follow-on configurations to address the technology needs was also evaluated. The final results were reviewed with NASA personnel and presented in final briefings.

2.1 TECHNOLOGY NEEDS EVALUATION

The technology needs were identified and then rated on importance to each of three mission classes: Space Station, Land Mobile Satellite System (LMSS), and Optical/Laser. These categories were treated as classes and not as specific configurations. Thus "LMSS" indicates any mission using large space structure with pointing requirements in fractions of a degree, a potential shape maintenance problem, and important structural modes below 1.0 Hertz. Since these mission classes have different requirements, the technology needs usually have different degrees of importance in each case. Numerical ratings from 0 to 10 were assigned to the technology needs based on the criteria:

- 0 for no application to mission
- 10 when absolutely required.

Since numerical ratings tend to be at least somewhat subjective, the effort concentrated on establishing reasonable rather than exact ratings. The resulting experiment was then judged for reasonableness and for coverage of the research areas.

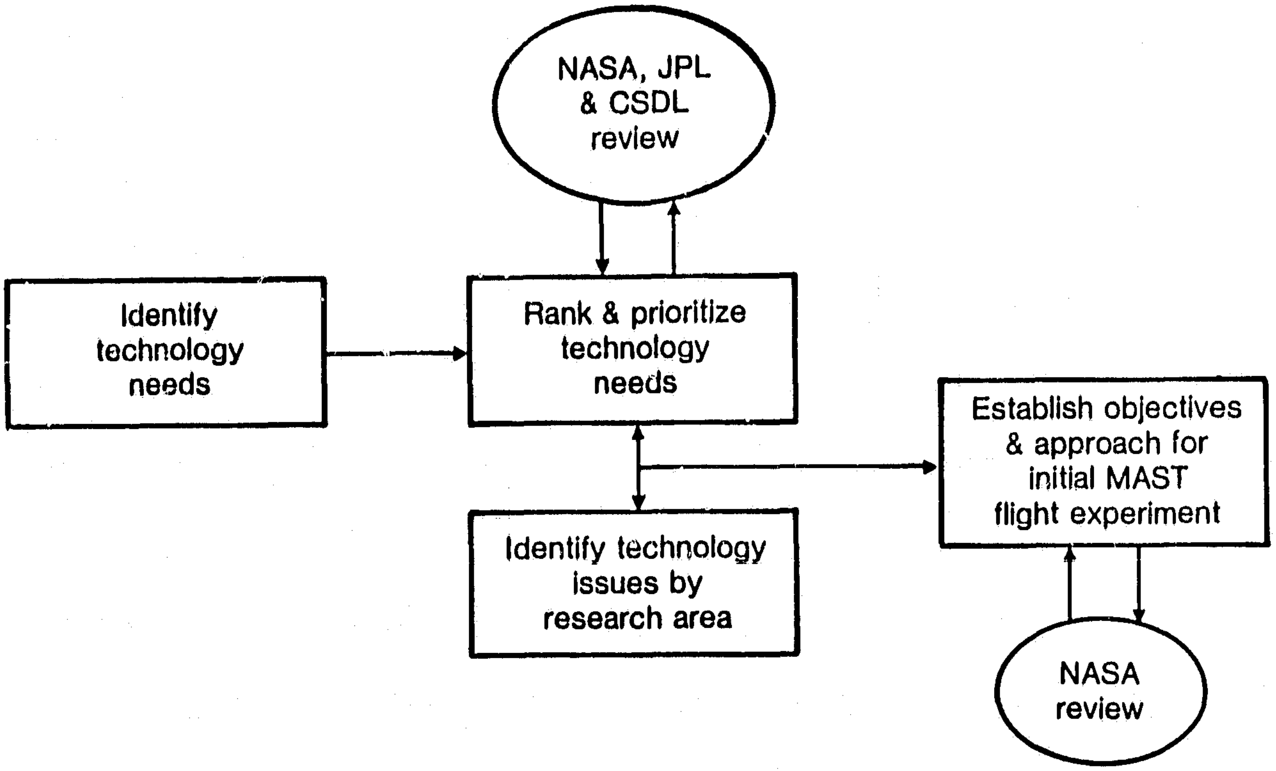

Figure 2-1 Experiment Objectives Analysis Approach

The numerical results were weighted to emphasize near-term missions and degree of NASA interest:

- X3 for space station
- X2 for LMSS
- X1 for optical/laser

Thus, although space-borne large lasers present some very interesting and challenging problems, that mission class was given a low weighting.

The technology needs along with their numerical ratings are shown in Tables 2-1 through 2-3. Category A consists of those needs which were assigned the highest priority. Need A1, actuators and sensors for active damping and vibration control, reflects the fact that there has been considerable effort toward structural control theory, but little effort toward control components to implement this theory on low frequency structures. Need A2 is for robust

Table 2-1. Highest Priority Technology Needs (Category A)

Technology Need	Space Station		LMSS		Optics /Laser	
	Rating	X3	Rating	X2	Rating	Total
A1. Actuators & sensors for active damping & vibration control	8	24	9	18	10	52
A2. Control system robustness to accommodate uncertainties in the structural model	9	27	8	16	9	52
A3. Techniques to control flexible large space systems	7	21	10	20	10	51
A4. Autonomous control of orbiter-attached flexible structure	10	30	6	12	1	43
A5. Accurate & reliable, analytically-derived, structural dynamic models for control system design	7	21	8	16	6	43
A6. Techniques to model & analyze deployment & retraction dynamics	8	24	8	16	3	43

Table 2-2. Second Priority Technology Needs (Category B)

Technology Need	Space Station		LMSS		Optics /Laser	
	Rating	X3	Rating	X2	Rating	Total
B1. Techniques to avoid adverse interactions among rigid body, static figure & vibration control systems	5	15	9	18	10	43
B2. Control of LSS during construction in space	9	27	5	10	1	38
B3. Techniques to enhance the accuracy of models by ground testing of subsections of the LSS	7	21	7	14	2	37
B4. Greater knowledge of the in-space disturbance environment & its resulting dynamic effects on the LSS	7	21	7	14	1	36
B5. Control techniques to accommodate operational changes in structural geometry & mass properties (step and/or continuous)	9	27	3	6	1	34

Table 2-3. Third Priority Technology Needs (Category C)

Technology Need	Space Station		LMSS		Optics /Laser	Total
	Rating	X3	Rating	X2	Rating	
C1. Techniques for static figure measurement & control	1	3	10	20	10	33
C2. Techniques to isolate severe vibration sources	4	12	6	12	8	32
C3. Actuators & sensors for static figure control	1	3	9	18	10	31
C4. Proven techniques for in-orbit identification of structural model (off-line or on-line)	2	6	7	14	9	29
C5. Definition of the role of passive damping	4	12	4	8	4	24
C6. Active control techniques to emulate high stiffness in a very flexible structure	2	6	2	4	2	12
C7. Techniques to rapidly slew & point agile LSS	0	0	1	2	9	11

control systems to accommodate structural model uncertainties. It should be noted that robust systems include simple low performance local velocity feedback techniques as well as the more sophisticated multivariable approaches. Need A3 reflects the fact that large flexible space systems will have modes with frequencies considerably lower than any encountered (or controlled) on existing systems. Need A4 deals with control of a large flexible system with a passive orbiter attached. Whereas A2 dealt with control systems to accommodate structural model inaccuracies, Need A5 is to improve the accuracy of the structural model. Need A6 also deals with better structural models, but specifically during deployment and retraction.

The dividing point between Category A and Category B, the second priority group, is somewhat arbitrary and could well change as the emphasis on various systems changes with time. Need B1, avoidance of adverse interactions between dynamic systems, was chosen as the breakpoint since, at the present time, the advanced missions that face severe dynamic interactions appear to be in the rather distant future. Needs B2 and B5 both deal with changing mass and geometry, but the latter would be in an operational system that required tighter control than the former. Need B3 recognizes that

it will not be possible to assemble and test very large space structures on the ground. It then follows that testing to support structural modeling will have to be performed on structural subsections. Greater knowledge of the large space structure disturbance environment, Need B4, is often overlooked as a problem, but the low frequency characteristics of disturbances such as man motion are not well-defined and may be significant in evaluating low frequency structural motion.

In the third priority group, Needs C1 and C3 deal with static figure or shape control. Considerable effort has been expended recently in designing antennas that do not require shape control. However, these antennas are "large" only by todays standards and not by future standards. It is doubtful that future antenna reflectors with dimensions of 100 meters or more can be deployed in earth's gravity, adjusted in shape to compensate for manufacturing tolerances, packaged for launch, and deployed in the zero gravity of space and still maintain exact shape. Some form of shape control will be required to adjust the initial shape as well as adjust for the low frequency environmental disturbances, such as thermal, which may continually cause small shape variations. Need C2, isolation of severe vibration is of prime interest to laser systems but could be required on a space station as the result of some unidentified manufacturing process. Need C4, structural model identification, will be very useful for future missions with very stringent control requirements, but the successful implementation of this technique seems to also be in the future. Passive damping, Need C5 is expected to play a role in future large space structures, but results to date indicate that it is ineffective for the very low frequencies which are the major concern. Needs C6 recognizes that some current work is considering the problem of stiffening very soft (weak) structure with active control, but it has yet to be determined that such structure can tolerate ground handling and launch environments. Finally, Need C7, rapid slewing, is of prime interest to military laser systems, but of no interest to space station.

Before relating the Needs to a specific experiment, the various possible MAST configurations are reviewed. The configurations are shown in Figure 2-2. Configuration 1 is the fully instrumented straight structure with control actuators at the tip only. These tip actuators can be used as exciters or in a simple local velocity feedback (LVFB) mode which does not require a digital computer. Configuration 1A has additional actuators and a digital computer so as to provide for a greater variety of control techniques. Configuration 2 uses an actuator to rotate the top section of the structure so as to add significant yaw modes. A crosspiece is added to Configuration 2 to form Configuration 3 which is expected to have the most complex set of modes in all three axes. The

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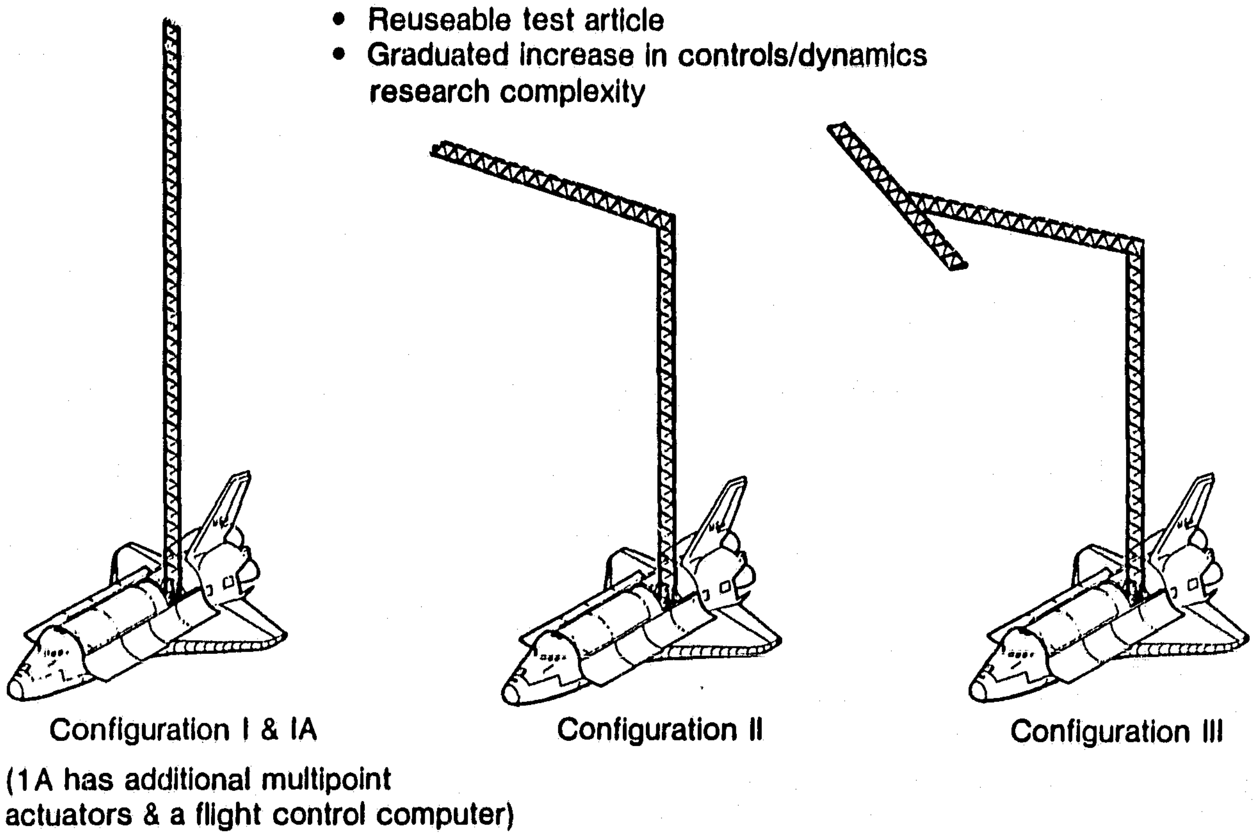

Figure 2-2. MAST Configurations

crosspiece rotating on the bent section should approximate the characteristics of an antenna dish on a support arm. Configurations 2 and 3 were not analyzed for dynamics, but sufficient design studies were conducted to establish feasibility (see Section 3.1)

The capability of the various configurations to address the technology needs is shown in Table 2-4. It should be noted that "addressed" means that progress can be made but the need will not necessarily be totally fulfilled. The dots on the table indicate that the need could be addressed by use of the basic structure if features or equipment in addition to that described above were to be added.

Inspection of Table 2-4 shows that Configuration 1 addresses four of the six A needs and four of the five B needs. The more

able 2-4. Technology Needs Addressed by MAST Configurations

	Requirement addressed by configuration			
	I	IA	II	III
CATEGORY A: HIGHEST PRIORITY				
A1 — Actuators & sensors for active damping & vibration control	✓	✓	✓	✓
A2 — Robust control systems which do not require an exact knowledge of the structural dynamics	✓	✓	✓	✓
A3 — Techniques for the control of large flexible space systems		✓	✓	✓
A4 — Techniques for the control & stabilization of orbiter-attached flexible structure		✓	✓	✓
A5 — Knowledge of potential structural modeling errors in large space structure	✓	✓	✓	✓
A6 — Techniques to model & analyze deployment & retraction dynamics	✓	✓	✓	✓
CATEGORY B: SECOND PRIORITY				
B1 — Control techniques to avoid adverse interactions between dynamic systems (rigid body pointing & stabilization, active structural damping, and/or shape control)		✓	✓	✓
B2 — Control techniques to tolerate changes in structural geometry (step and/or continuous)	✓	✓	✓	✓
B3 — Techniques to enhance structural models by ground testing structural subsections	✓	✓	✓	✓
B4 — Confirmation of the LSS disturbance environment & definition of the resulting structural motions	✓	✓	✓	✓
B5 — Techniques for the control of structure during deployment and/or assembly	✓	✓	✓	✓
CATEGORY C: THIRD PRIORITY				
C1 — Actuators & sensors for shape controls		•	•	•
C2 — Techniques to isolate severe vibration sources		•	•	•
C3 — Techniques for the measurement & control of the shape of large antennas or optical systems		•	•	•
C4 — Techniques for in-orbit identification of the structural model		✓	✓	✓
C5 — Definition of the role of passive damping		•	•	•
C6 — Techniques to fix up very "soft" structure with active control				•
C7 — Techniques to rapidly slew & point agile LSS				

✓ Addressed • Could be addressed by further expansion

complex configurations address all of the A and B needs. The limitation on Configuration 1 is the use of single point actuation instead of multiple point and the lack of a digital computer to exploit the multipoint actuation capability. It might be concluded that it would make more sense to proceed directly to the more complex configurations and not bother with Configuration 1. However, this is not recommended. Technical needs would be served best by an orderly buildup in complexity which avoids the temptation to try to accomplish too much too fast. Returning to Table 2-4, the only need which cannot be addressed by even expanded configurations, is C7, agile large systems with slew requirements. This is because neither the Orbiter or the proposed experimental structure are compatible with rapid maneuvers.

2.2 RESEARCH AREAS

An independent approach to identifying experiment objectives was taken by having a technical specialist assemble an exhaustive list of research areas of interest to controls and structural dynamics for large space systems. The results are presented in Tables 2-5 through 2-8 along with a brief description of the technology deficiency and its importance.

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Table 2-5. RESEARCH AREA 1 - STRUCTURAL DYNAMIC MODELING ISSUES

TECHNOLOGY ISSUES	TECHNICAL SIGNIFICANCE	
	TECHNOLOGY NEEDS/DEFICIENCIES	HOW IS IT IMPORTANT AND WHY
A. MODAL MODEL UNCERTAINTY 1. MODAL BEHAVIOR a. Modal Frequencies b. Modal Slopes (Displacements and Rotations)	Accurate modeling techniques for LSS are lacking. Assumptions are employed which have no emphirical basis.	Control system stability and performance depend strongly on accurate modeling.
2. STRUCTURAL PROPERTIES a. Inherent Damping (Joints and Materials) b. Mass Properties c. Stiffness	Behavior of a joint dominated structure in a zero-g environment is unknown.	Control system stability and performance depend strongly on accurate modeling.
B. VALIDITY OF LINEAR MODELS 1. NONLINEAR EFFECTS a. Amplitude Sensitivity b. Reciprocity	Basic question remains pertaining to the accuracy of linear models.	Control system stability and performance depend strongly on accurate modeling.
C. VALIDITY OF MODAL SYNTHESIS 1. MODAL SYNTHESIS TECHNIQUES	Accurate modeling techniques for LSS based on emphirical data are lacking.	Control system stability and performance depend strongly on accurate modeling.
D. CONTINUUM MODELING 1. PDE MODELS	Basic question remains pertaining to the accuracy of PDE models	Control system stability and performance depend strongly on accurate modeling.
2. TRAVELING WAVES	Basic question remains pertaining to the accuracy of traveling wave models.	Control system stability and performance depend strongly on accurate modeling.
3. BOUNDARY CONDITIONS	Boundary condition matching required for PDE models and traveling waves.	Control system stability and performance depend strongly on accurate modeling.

Table 2-6. RESEARCH AREA 2 - CONTROL ISSUES

TECHNOLOGY ISSUES	TECHNICAL SIGNIFICANCE	
	TECHNOLOGY NEEDS/DEFICIENCIES	HOW IS IT IMPORTANT AND WHY
A. CONTROL ALGORITHM PERFORMANCE 1. ROBUSTNESS a. Model Reduction b. Model Error Compensation c. Gain/Phase Margins	Robustness data for multi-input/multi-output LSS control systems is non-existent.	Permits practical LSS design in the face of parameter uncertainty by providing a guaranteed stability margin.
2. ACTIVE DAMPING	Required for low performance, high reliability control for uncertain LSS systems.	A high reliability control system is needed for stability augmentation.
3. MULTIPOINT CONTROL	All LSS will employ multipoint control systems - control system performance data is non-existent.	Validation of the active control system technology is necessary to insure the success of LSS missions.
4. DISTURBANCE REJECTION (ACTIVE ISOLATION)	Isolation is required to isolate the quiet structure from noisy apparatus.	The quiet/noisy isolation concept simplifies many LSS control problems.
5. ACTUATOR/SENSOR PLACEMENT	Required for effective LSS control.	Without proper actuator/sensor placement, the control system will not function.
B. ADVERSE SUBSYSTEM INTERACTION 1. DECENTRALIZED CONTROL	Needed to handle conflicting control requirements of different subsystems. Provides evolutionary growth capability.	Permits the methodological design of LSS control systems with conflicting requirements.
2. CONTROL HEIRARCHY	Needed to provide a steady evolution of control performance in the face of parameter uncertainty.	Provides high reliability, high performance control.
C. CLOSED-LOOP CONTROL DURING GEOMETRY CHANGES 1. DEPLOYMENT CONTROL	Deployment control is required for all Shuttle-borne LSS.	Stability must be maintained during deployment.
2. GAIN SCHEDULING	Provides a system to handle known parameter changes.	Ensured stability through a wide range of known parameter variations.
3. ADAPTIVE CONTROL	Provide a system to handle unknown parameter changes.	Provides stability and control through a range of unknown parameter variations.

Table 2-6. RESEARCH AREA 2 - CONTROL ISSUES (CONTINUED)

TECHNOLOGY ISSUES	TECHNICAL SIGNIFICANCE	
	TECHNOLOGY NEEDS/DEFICIENCIES	HOW IS IT IMPORTANT AND WHY
D. STATIC SHAPE CONTROL 1. SHAPE CONTROL ALGORITHMS	Reflectors, antennas, and optical systems will require some means of shape control.	Pointing requirements cannot be met without static shape control.
2. ACTUATORS/SENSORS	Actuation and sensing hardware for shape control are lacking.	Shape control systems need proper sensing and actuation to meet mission requirement.
E. CONTROL SYSTEM COMPONENTS 1. SENSORS a. Rate Gyro b. Position Sensor	Sensors and actuators for control components are lacking.	Control algorithms cannot function without effective hardware.
2. ACTUATORS a. Torque Wheels b. Scissored CMG c. Proof Mass Actuator	Sensors and Actuators for control components are lacking.	Control algorithms cannot function without effective hardware.
3. FLIGHT COMPUTER	Complex control algorithms require a flight computer.	All LSS require multipoint control systems. A flight computer is necessary for multipoint control.
4. ANALOG/DIGITAL CONTROL	Centain control algorithms are best implemented digitally and others analog.	Provides greater reliability in control system development.
5. ISOLATORS a. Magnetic b. Mechanical c. Tuned Vibration	Isolation is required to isolate the structure from noisy apparatus.	The quiet/noisy isolation concept simplifies many LSS control problems
F. CONTINUUM CONTROL 1. PDE CONTROL	Uniform structures and extremely large structures can be modeled by partial differential equations.	Provides an alternate means to model and control LSS.
2. TRAVELING WAVES	Uniform structures and extremely large structures can be characterized by traveling waves.	Traveling waves introduce delays in the system response and can lead to instability.

Table 2.6. RESEARCH AREA 2 – CONTROL ISSUES (CONTINUED)

TECHNOLOGY ISSUES	TECHNICAL SIGNIFICANCE	
	TECHNOLOGY NEEDS/DEFICIENCIES	HOW IS IT IMPORTANT AND WHY
G. INTEGRATED DESIGN (CONTROL MECHANIZATION)	Integrated design of structures and control systems.	Provides a true control configured spacecraft.
H. AGILE SYSTEMS	The control of agile systems requires the development of new algorithms.	The ability to rapidly slew and point a spacecraft is necessary for some military missions.
I. RCS FLEXIBLE STRUCTURE CONTROL DEVELOPMENT (REVERSE CONTROL)	Firing of the RCS will cause structure/Orbiter interactions.	The structure Orbiter interactions must be analyzed to prevent instability.

Table 2-7. RESEARCH AREA 3 - SYSTEM IDENTIFICATION ISSUES

TECHNOLOGY ISSUES	TECHNICAL SIGNIFICANCE	
	TECHNOLOGY NEEDS/DEFICIENCIES	HOW IS IT IMPORTANT AND WHY
A. MEASUREMENT OF OPEN-LOOP DYNAMICS 1. Control Plant Identification 2. Amount of A-Priori Data 3. Parameter Identification Control Plants 4. Parameter Identification Structural Model 5. Universal Identification 6. Disturbance Identification 7. Degree of Identification 8. Static Process Identification 9. Dynamic Process Identification 10. Continuous Model 11. Discrete Model 12. Deterministic Identification 13. Probabilistic Identification	Systematic identification of open-loop dynamics.	Knowledge of modal parameters permits the design of high performance with adequate stability margins. Verification of modal models provides empirical verification of theory.
B. MEASUREMENT OF CLOSED-LOOP DYNAMICS 1. Input-Output Variable ID versus Internal State ID 2. Identification Signal (Series) 3. Direct Identification 4. Recursive Identification 5. On Line ID 6. Off Line ID 7. Identifier Relization 8. Stale Data 9. Current Data 10. Frequency Band Separation of Identification Data	Systematic identification of closed-loop dynamics.	Verification of control system performance. Determination of closed-loop poles and zeros allows the development of advanced control concepts.
C. CONTINUUM MODEL IDENTIFICATION 1. Traveling Wave ID in Large Systems 2. PDE Model Identification	Systematic identification of continuum models	Verification of continuum model dynamics

Table 2-8. RESEARCH AREA 4 - DYNAMICS ISSUES

TECHNOLOGY ISSUES	TECHNICAL SIGNIFICANCE	
	TECHNOLOGY NEEDS/DEFICIENCIES	HOW IS IT IMPORTANT AND WHY
A. ACCURATE DEPLOYMENT MODELING 1. DEPLOYMENT a. Extension b. Retraction	Accurate modeling of the large space system during deployment.	Stability of the LSS must be maintained during deployment.
2. GEOMETRY CHANGES a. Additions b. Construction c. Mounting Changes	Accurate modeling of the LSS during geometry changes.	Stability of the LSS must be maintained during geometry changes.
3. MASS CHANGES	Accurate modeling of the LSS during mass changes.	Stability of the LSS must be maintained during mass changes.
B. DOCKING	Accurate modeling of the docking procedure.	Maintenance of stability and performance during docking.

These issues were summarized to a more compact form and compared with the Technology needs of Table 2-4. The ability of the various configurations to address the Research issues was also evaluated. Tables 2-9 and 2-10 present the results. It can be seen that all of the research areas can be related to a technology need. Further, the ability of the various configurations to address the issues is the same as it was for the technology needs: Configuration 1 addresses a significant portion of the issues, the more complex configurations address most of the issues, and further expansion could address all of the issues except agile systems.

Table 2-9. RESEARCH AREAS ADDRESSED BY MAST CONFIGURATIONS

	Technology Need	Addressed by Mast Configuration			
		I	IA	II	III
Modeling					
• Modal uncertainty — Modal behavior	A5	✓	✓	✓	✓
— Structural properties	A5		•	•	•
• Validity of linear models — Nonlinear effects	A5	✓	✓	✓	✓
• Modal synthesis — Validity of modal synthesis techniques	B3	✓	✓	✓	✓
• Continuum modeling — PDE models	A5	✓	✓	✓	✓
— Traveling waves	A5	✓	✓	✓	✓
— Boundary conditions	A5	✓	✓	✓	✓
Systems Identification					
• Open loop ID — Measurement of open loop dynamics	C4	✓	✓	✓	✓
• Closed loop ID — Measurement of closed loop dynamics	C4		✓	✓	✓
• Continuum model ID — Measurement of continuum model dynamics	C4	✓	✓	✓	✓
Dynamics					
• Deployment modeling — Geometric changes	A6	✓	✓	✓	✓
— Mass changes	A6		•	•	•

✓ Addressed • Could be addressed by further expansion

Table 2-10. RESEARCH AREAS ADDRESSED BY MAST CONFIGURATIONS

	Technology Need	Addressed by Mast Configuration			
		I	IA	II	III
Control					
• Control algorithm performance — Robustness	A2	✓	✓	✓	✓
— Active damping	A3	✓	✓	✓	✓
— Multipoint control	A3		✓	✓	✓
— Disturbance rejection	A3		✓	✓	✓
— Actuator/sensor placement	A3	✓	✓	✓	✓
• Subsystem interaction — Decentralized control	B1		✓	✓	✓
— Control hierarchy	B1		✓	✓	✓
• Control during geometry change — Deployment control	B5	✓	✓	✓	✓
— Gain scheduling	B5		✓	✓	✓
— Adaptive control	B5		✓	✓	✓
• Static shape control — Shape control algorithm	C1		•	•	•
— Actuators/sensors	C3		•	•	•
• Control system components — Sensors	A1	✓	✓	✓	✓
— Actuators	A1	✓	✓	✓	✓
— Computers	A3		✓	✓	✓
• Continuum control — PDE control	A3		✓	✓	✓
— Traveling waves	A3		✓	✓	✓
• Integrated design — Integrated control mechanism	A1				
• Agile systems — Agile systems control	C7				
• RCS control — RCS control of flexible structure	A4		•	•	•

✓ Addressed • Could be addressed by further expansion

SECTION 3

PRELIMINARY DESIGN AND ANALYSIS

The SCE preliminary design was revised to incorporate new requirements established by NASA/LaRC, the most significant of which was to ensure compatibility with STEP. Structural analysis of the revised deployable truss configuration and the new support structure was performed and the SCE mass properties were updated. The SCE or MAST controls philosophy and the various avionics interfaces were re-examined. This section presents the results of these activities.

3.1 REQUIREMENTS

The structural requirements for the MAST test as established by NASA/LaRC are shown below.

- Compatible with STEP experiment carrier
- Size and stiffness
  - Approximately 2×10^7 N-M^2
  - 1.2-1.4 meters depth
- Compaction ratio

  $\left(\frac{\text{deployed length}}{\text{stowed length}}\right)$ = between 20 and 25
- Test article design to withstand vernier RCS loading in lieu of primary RCS.
- 60 meters in length
- Employ high precision beam joints (zero free play)
- Sequentially deployable truss beam
- Lowest natural frequency $\geq$ 0.15 Hz

3.2 PRELIMINARY DESIGN

The baseline structural test article configuration selected in Parts I and II of the study was the Convair designed deployable tetrahedral truss with a diamond cross section. This remains the baseline configuration although a significant change involved eliminating the carpenter tape hinges. The need to double fold the stowed structure no longer exists and the open diamond structure reduces manufacturing cost (fewer joints) and provides

increased flexibility relative to available space for mounting actuators, instrumentation or anything that more complex configurations might require (e.g., the astromasts of Configuration III). Other changes involved revisions to the support structure to ensure compatibility with STEP. The revised SCE concept is shown in Figure 3-1. The changes are described in the following sub-sections.

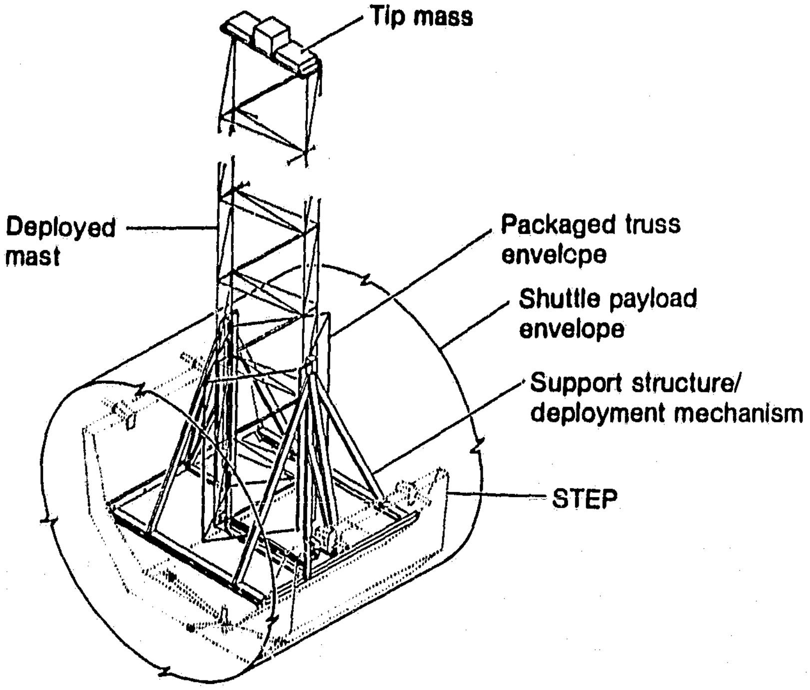

Figure 3-1. Revised Space Construction Experiment (SCE) Concept

3.2.1 SUPPORT STRUCTURE. The support structure shown in Figure 3-2 is made up of two aluminum box beams in the longitudinal direction joined to two aluminum I-beams in the transverse direction. The roll frames are joined to the longitudinal box beams and deployment structure while the pitch frames are joined to the I-beams and the deployment structure. This forms an open rectangular structure divided by the deployment structure and provides easy access to electronics packages mounted on the STEP pallet.

The entire structure is tied to the STEP pallet at eight hard points with pyrotechnic separation nuts should jettison of the experiment become necessary. A shuttle Remote Manipulator System (RMS) standard grapple fixture (SPAR Part No. 51196F1-3) will be located on the support structure. After the separation nuts have been activated, this grapple fixture will allow for jettison of the support structure and payload from the STEP pallet and cargo bay, using the RMS fitted with a standard end effector.

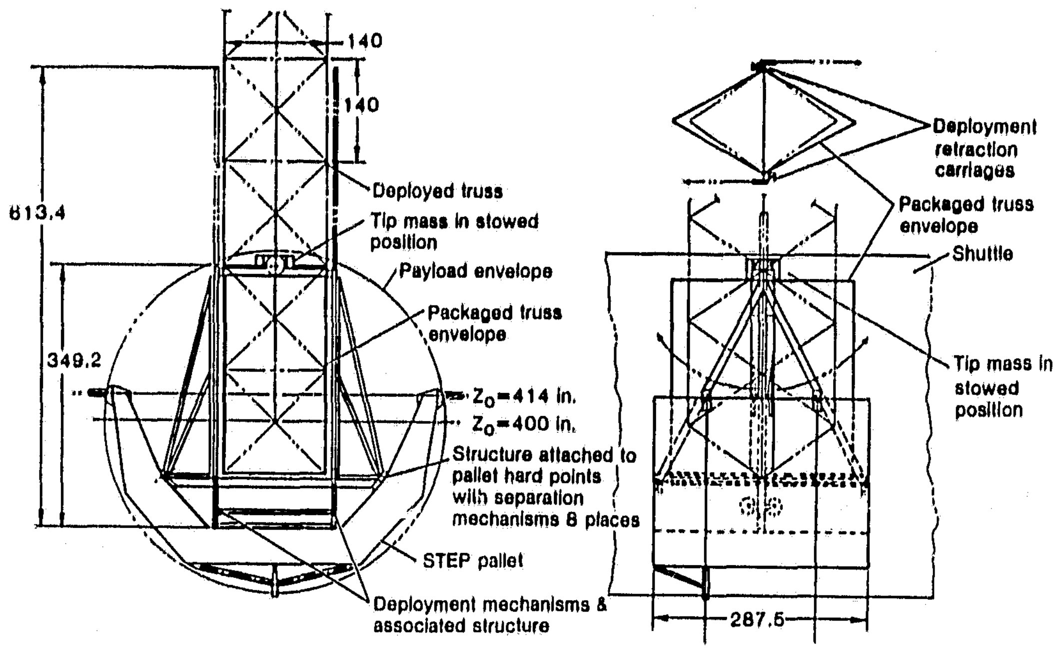

Figure 3-2. Deployable MAST on STEP

3.2.2 DEPLOYABLE TRUSS. The revised truss structure, shown in Figure 3-3 has a packing or compaction ratio of 22:1 and has three different types of joints, the carpenter hinge having been eliminated. Four configurations have been examined to ensure that they can be packaged individually on a single STEP pallet. Configuration I is a simple straight deployable beam intended for the first flight. Configurations IA, II and III are relatively simple follow-on concepts intended to address more complex controls and dynamics issues (see Section 2.0).

3.2.2.1 Configuration I. The general arrangement for Configuration I is shown in Figures 3-4 and 3-5. The drawing shows the initial stage of the truss deployment with the first two bays deployed. Basically the system consists of a truss deployment rail structure with extension rails, two motorized carriages, two electric cable take up reels and the deployable truss with tip mounted augmentation unit and mass. The rails contain tracks for truss and carriage rollers and gear racks for the carriage drive pinion. A trip arm attached to each overcenter hinge is used to initiate the folding sequence of the overcenter hinge longerons during truss retraction. Note also the RMS receptacles in Figures 3-4 and 3-5. The RMS is used to perform the following functions: a) rotation of the folded deployment rail assemblies; and b) rotation of the overcenter hinge tripper support arms.

Linear deployment and retraction of the truss is accomplished by the movable carriages. Each carriage contains a drive motor, a solenoid operated latch and two overcenter hinge tripper mechanisms that unlatch the overcenter hinges of the longerons during retraction. The deployment and retraction sequence is shown on Page 3-5.

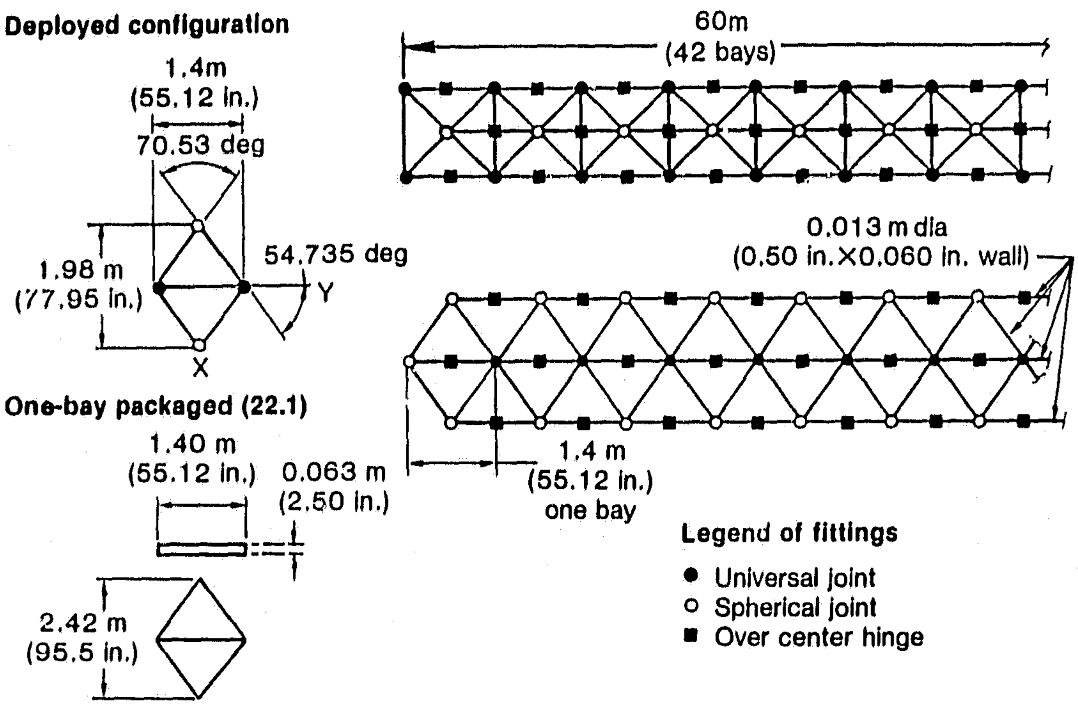

Figure 3-3. Revised Tetrahedral Truss Geometry

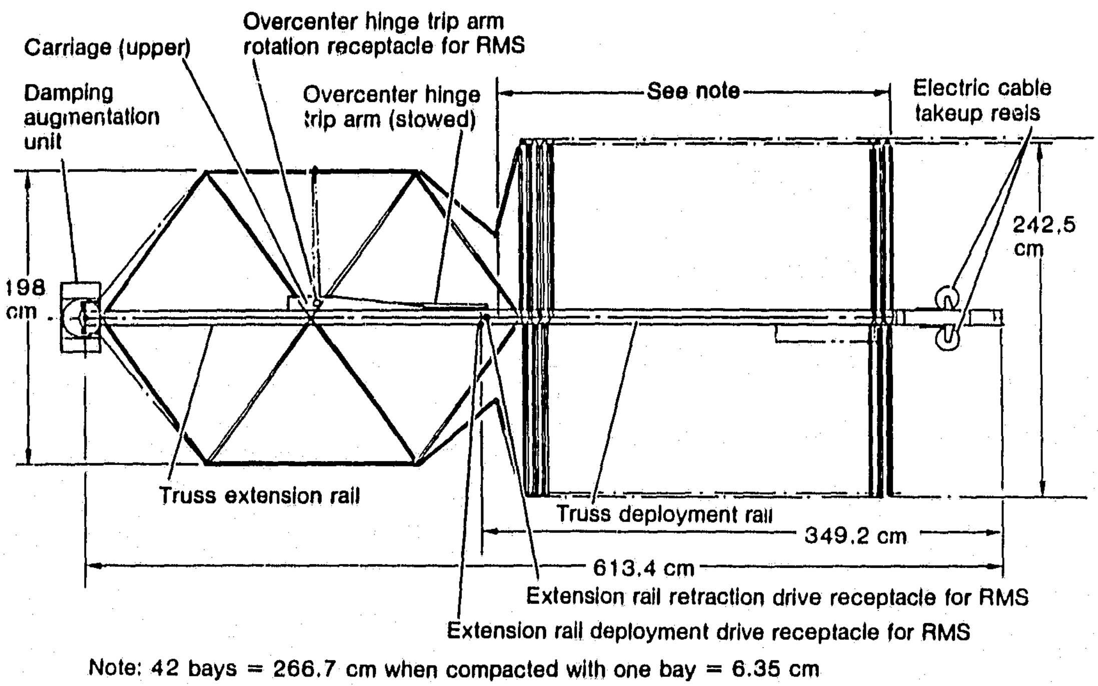

Figure 3-4. Deployable Truss General Arrangement I

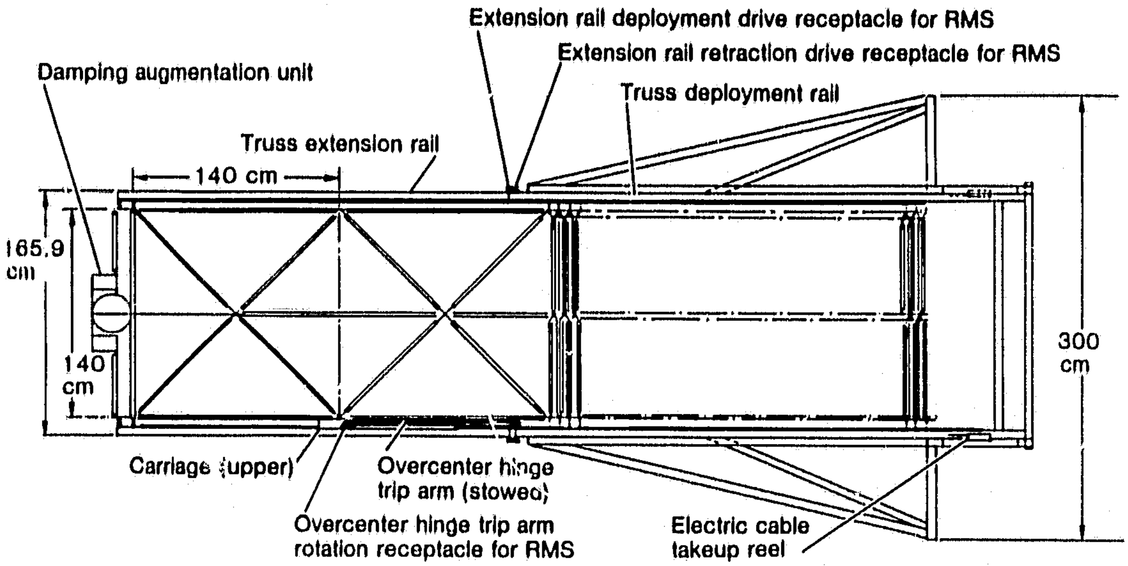

Figure 3-5. Deployable Truss General Arrangement 2

Deployment

- Rotate extension rails with RMS
- Move motorized carriages to extension rails
- Rotate overcenter hinge trip arms on carriages with RMS
- Deploy 42 bays of truss one at a time with motorized carriages

Retraction

- Retract 42 bays of truss one at a time with motorized carriages
- Rotate overcenter hinge trip arms on carriages to stowed position with RMS
- Move motorized carriages to stowed positions on deployment rails
- Rotate extension rails to stowed position with RMS

- No EVA required

The geometry for one packaged truss bay is shown in Figure 3-3. All tubes are 0.5 inch diameter. The tubes for bays 15, 23 and 29 are modified by adding a beam structure as shown in Figure 3-6. The tubes for bays 6, 11, 12, 18, 20, 26, 32, 35, 38 and 40 are modified for accelerometer installation as shown in Figure 3-7. Clearances between the modified tubes and the longeron overcenter hinges are held to a minimum to maximize packaging efficiency. These modifications are intended to provide mounting surfaces for additional torque wheel actuators and instrumentation required for follow-on flight configurations.

The end of the deployable truss is equipped with a special support frame for the damper sets and tip mass (Figure 3-8). Six damper

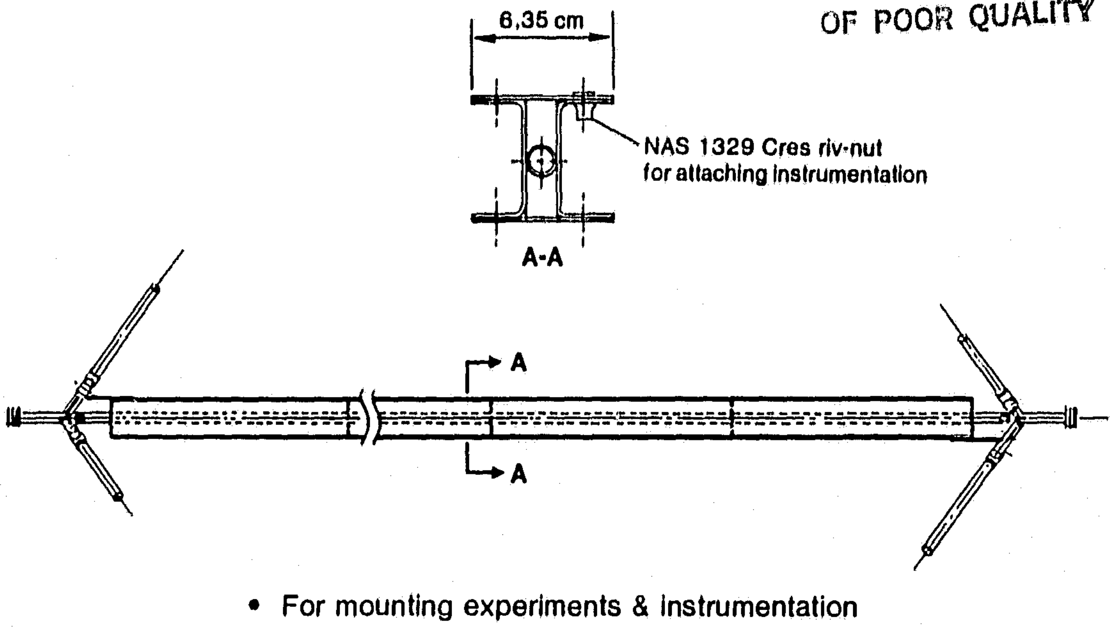

Figure 3-6. Modified Cross Members of Truss for Mounting Experiments and Instrumentation

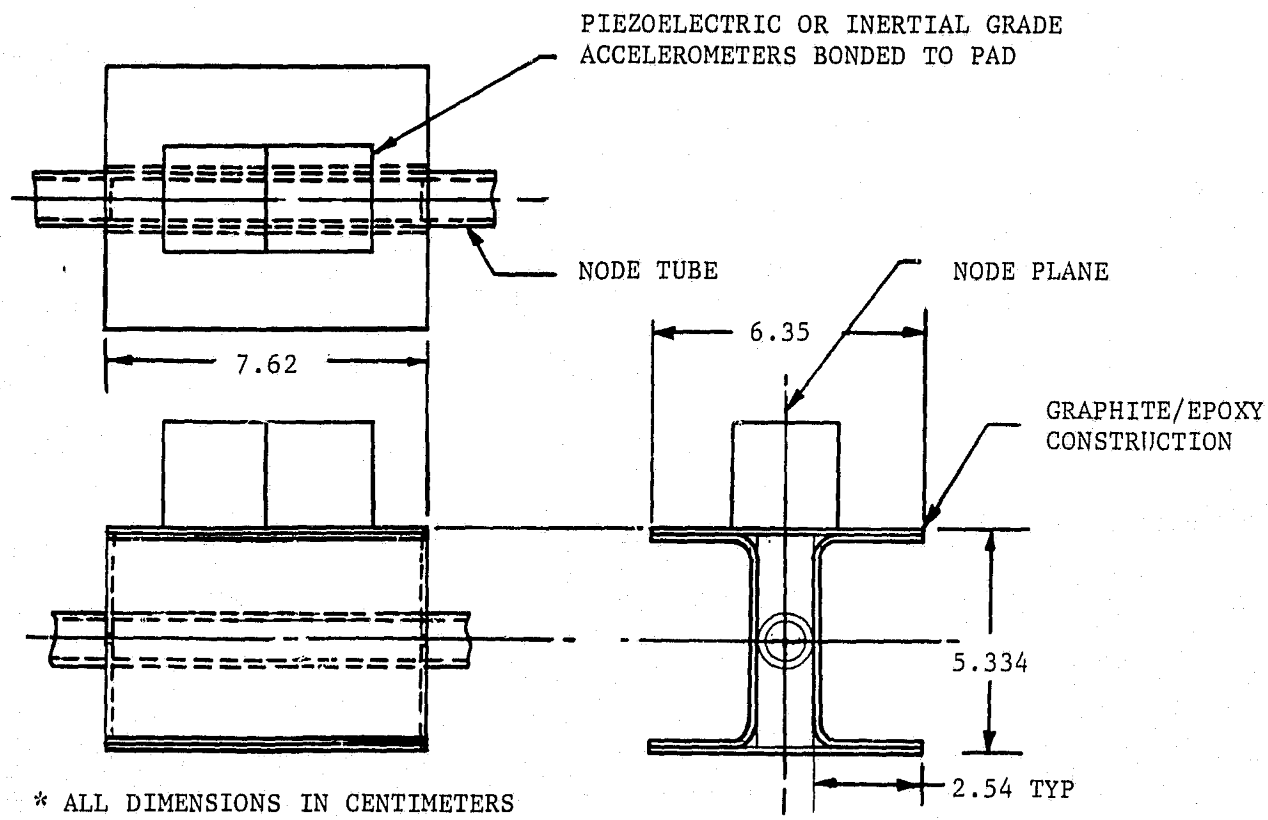

Figure 3-7. Accelerometer Installation

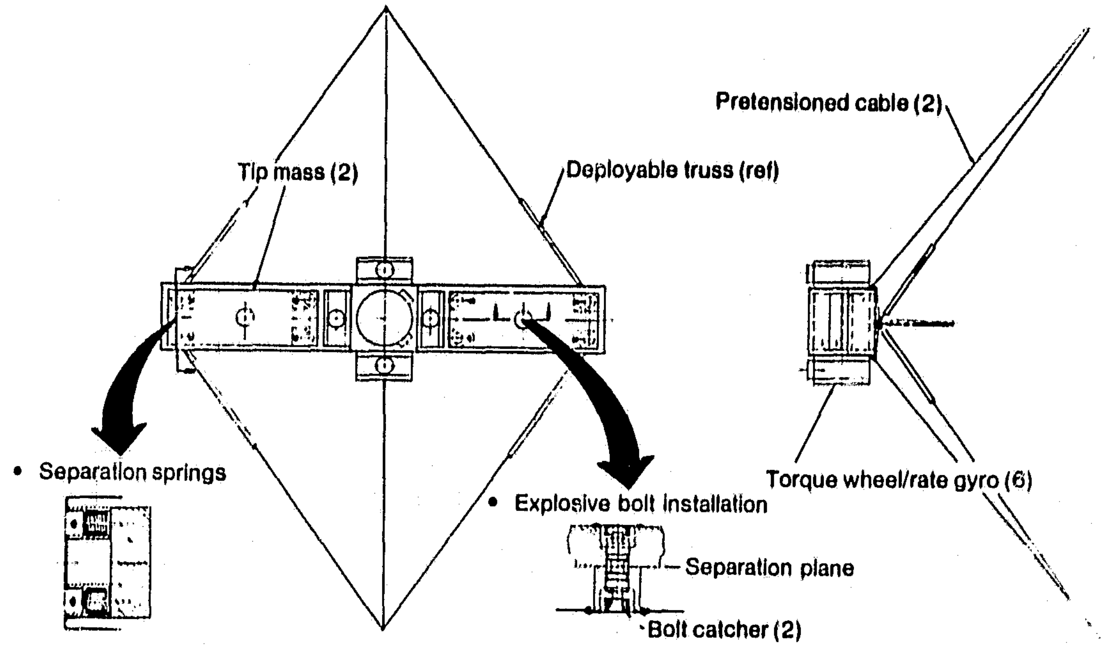

Figure 3-8. Damping, Excitation and Tip Mass Assembly

sets, each consisting of a torque motor, rotor, and rate gyro sensor are mounted in a housing such that there are two damper sets per axis. These two sets provide the capability to evaluate active structural damping techniques and excite structural modes.

Two steel bars are attached to the support frame, each by an explosive bolt. The steel bars provide the added mass necessary to bring the total weight of the tip package to 100 kg. However, the tip masses must be jettisoned to provide a favorable center of gravity of the experiment for payload jettison in the event of a retraction failure of the truss. The tip masses are jettisoned by firing explosive bolts, allowing separation springs to accomplish the jettison.

The support frame is supported at the center by two pre-tensioned cables attached to the truss. These cables react the moment loads that will be generated by the torque wheels in the damper sets during damping or excitation operations.

3.2.2.2 Configuration IA. Structurally, Configuration IA is the same as Configuration I. In addition to the control actuator at the tip of the truss, Configuration IA has torque wheel actuators at bays 15, 23 and 29 plus a digital computer to explore multipoint actuation capability.

3.2.2.3 Configuration II. Configuration II is shown deployed in Figure 3-9. This configuration uses a pivot and latch mechanism to articulate a portion of the top of the truss so as to provide significant modes in the yaw axis.

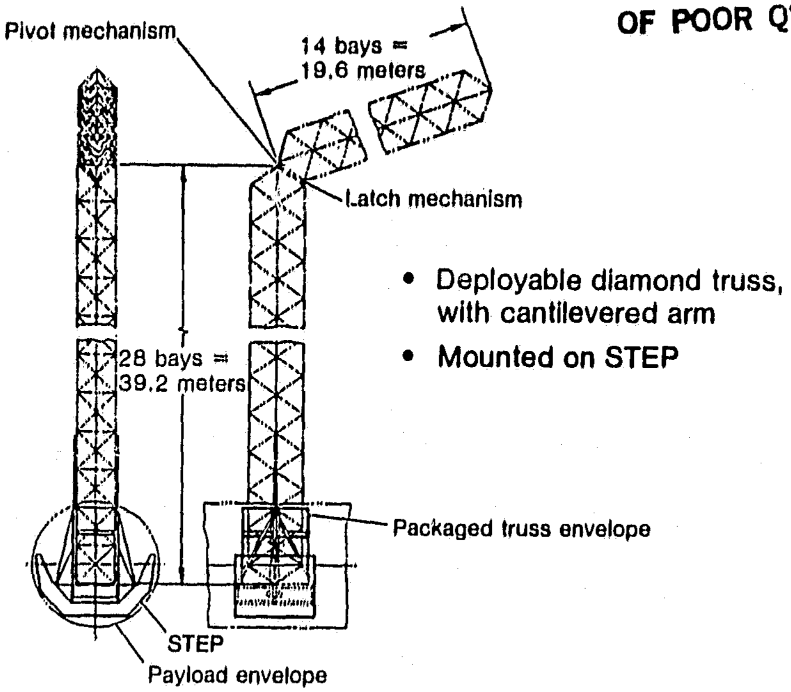

Figure 3-9. SCE - Configuration II

3.2.2.4 Configuration III. Configuration III is shown deployed in Figure 3-10. This is the same as Configuration II with Astromasts that deploy as a cross piece to provide the most complete set of modes in all three axes. This arrangement will exhibit some of the modal behavior of a large antenna dish deployed from a support arm and a feed mast. The ability to package Configuration III within the volume limitation of a single STEP pallet has been verified. The two Astromast canisters mounted on an internal platform are shown in Figure 3-11.

3.3 CONTROLS AND AVIONICS INTERFACES

3.3.1 MAST CONTROLS FUNCTIONS. The MAST controls are required to perform the functions of:

a. Carriage advance.

b. Carriage retract.

c. MAST tip torque actuation.

d. MAST tip torque damping.

e. Structural motion sensing.

f. Structural stress sensing.

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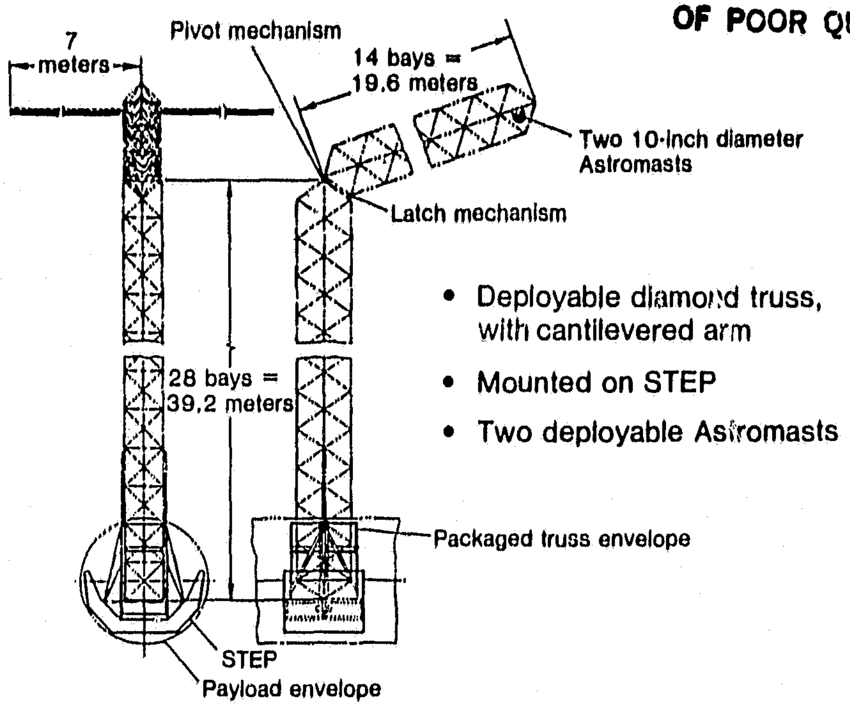

Figure 3-10. SCE - Configuration III

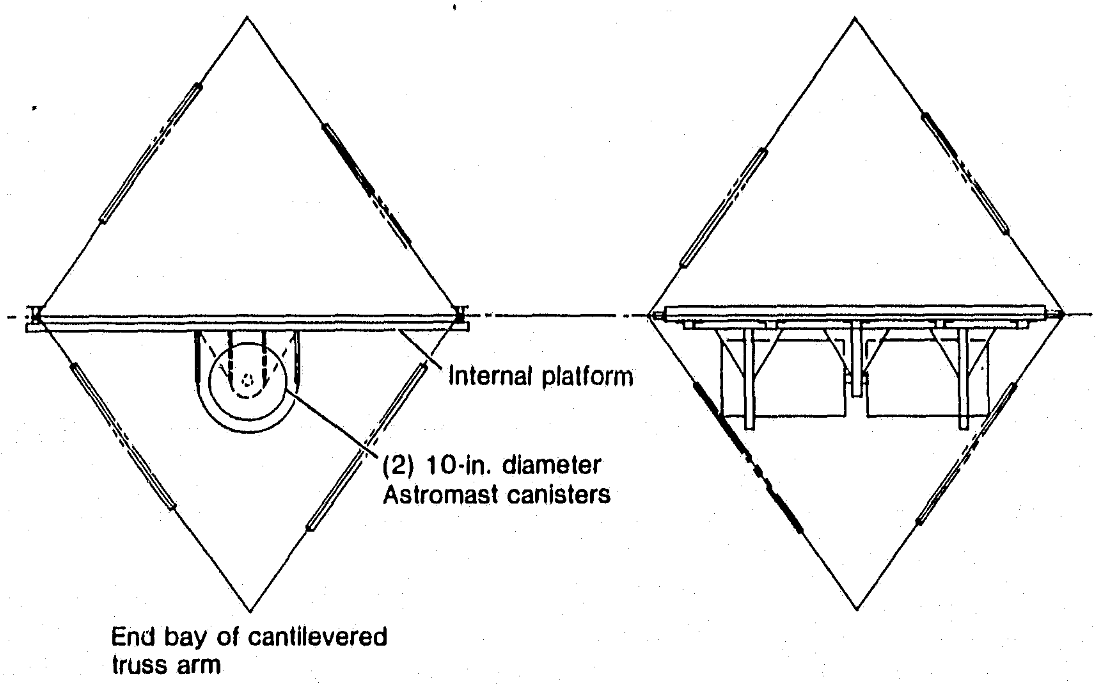

Figure 3-11. SCE - Configuration III Astromast Installation

g. Structural thermal sensing.

h. Power filtering and conversion.

i. Power control.

j. MAST system safety

k. Expansion capability for follow on advanced structural experimental tests.

3.3.2 MAST CONTROLS PHILOSOPHY. A fundamental controls philosophy criterion is that the MAST controls avionics shall not mask the basic structural behavior and response. If the MAST structural response is modified by addition of avionics units and cabling, the modified response shall be predictable and the basic structural response shall be extractable from the MAST experimental data. A fringe benefit of modified structural response due to the addition of avionics units and cabling, is the experimental data base available for future provision of avionics on space structures.

An optimum avionics functional partitioning is realized by utilizing the STEP avionics facilities for MAST supervisory control, data management, prime power control, and system safety. The MAST controls avionics provides the MAST carriage operations and experiment control loop functions along with sensor data digitizing.

The MAST controls philosophy utilizes the STEP command and control processor for MAST supervisory control by the mission specialist from the Orbiter aft flight deck (AFD) operator keyboard and display unit.

The STEP data management processor provides the MAST data interrogation and reception via the STEP digital I/O, data processing, formatting, and recording. The STEP data management processor inputs the mission specialist data display, provides the ground data transmission, and makes pertinent data available to the Orbiter avionics and crew via the Orbiter payload data interleaver (PDI).

An extension of the STEP power control is provided by the MAST 28 VDC power switch (located in the STEP power control and distribution box) control by the mission specialist from the AFD Standard Switch Panel (SSP). Remote MAST load switching is controlled from the STEP command and control processor.

In order to reduce the MAST deployment cable flexing, the impact on MAST structure dynamics, and the complexity of harness routing and installation on the structure, hardware interconnections along the MAST structure are minimized by:

a. Utilizing serial digital control and data busses.

b. Using self clocking data to eliminate the requirement for a clock bus.

c. Locating digital bus interface units at convenient truss bays for short run sensor harnessing.

d. Utilizing remote load power switching on the MAST 28 VDC power bus.

Intelligent digital bus interface units utilizing microprocessor (μP technology provide the required capabil-ty and flexibility for bus and sensor/actuator interfaces in a low mass and volume suitable for truss mounting.

3.3.3 <u>SHUTTLE ORBITER/STEP AVIONICS INTERFACES</u>. The Orbiter and STEP avionics block diagram is presented in Figure 3-12. It was derived from information provided by NASA/LaRC, and from the <u>Space Shuttle System Payload Accommodations</u>, JSC 07700, Vol. XIV.

3.3.3.1 <u>Command And Control Interfaces</u>. The command and control supervisory functions for the MAST experiment are conducted as:

a. Mission specialist enters operator instructions with AFD keyboard and monitors responses with associated display.

b. Command and control processor software acts according to operator instructions and transmits control words over truss serial command bus via experiment digital I/O.

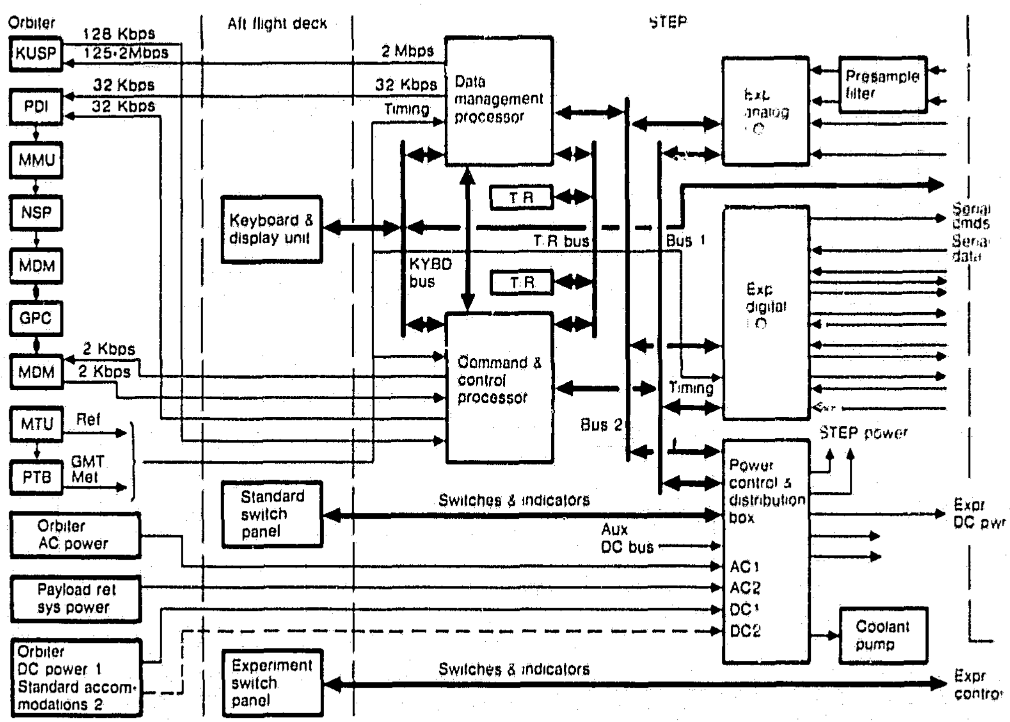

Figure 3-12. STEP/Orbiter Avionics Interface

c. Control functions include: Remote Device Power Activate/Deactivate, Carriage Advance Command, Carriage Retract Command, Torque Actuator Excitation Commands, Torque Actuator Damp Commands, Sensor Gain Change Commands.

d. Command and control data is available to the Orbiter General Purpose Computer (GPC) and crew displays as required, (e.g., during RMS operations) through the Orbiter PDI 32 KBPS channels.

e. Orbiter commands to STEP and command responses from STEP are provided by the Orbiter Multiplexer Demultiplexer (MDM) 2 KBPS channels.

f. Ground instructions can be entered via the Ku-band signal processor 128 KBPS channel or by S-band to the MDM 2 KBPS channel.

3.3.3.2 Data Management Interfaces. The data management functions for the MAST experiment are conducted by:

a. Mission specialist modifies data management operations as appropriate from the AFD keyboard and display unit.

b. Data management processor accesses MAST data from truss serial data bus via experiment digital I/O by sending a transmit command to the appropriate MAST bus interface unit over the truss serial command bus.

c. Received MAST data is processed, formatted and stored on STEP tape recorder, and is transmitted to the ground over the Ku-band signal processor 2 MBPS channel or S-band PDI 32 KBPS link as appropriate.

d. MAST Processed data is available to the Orbiter GPC and crew displays as required over the PDI 32 KBPS channel.

3.3.3.3 Electrical Power Interfaces. The MAST 28 VDC power is provided by:

a. AFD SSP operator controls availability of truss power bus 28 VDC from Orbiter located power sources.

b. STEP command and control processor controls remote load switching from truss power bus over serial command bus via experiment digital I/O.

3.3.3.4 System Safety Interfaces. Reliability and safety are insured by the following provisions:

a. Mission specialist can control truss deployment and retraction truss device power, and experiment activation via STEP command and control processor.

b. Truss carriage drive has redundant motors for reliable retraction drive.

c. AFD experiment switch panel hard wired to jettison tip mass in case of shuttle bay MAST retraction failure.

d. Orbiter crew, with RMS, can jettison MAST (with tip mass previously jettisoned) from STEP.

3.3.4 STEP/MAST AVIONICS INTERFACES. A very simple avionics physical interface between STEP and MAST has been established (Figure 3-13). It consists of:

a. A single control bus.

b. A single data bus.

c. A 28 VDC supply bus and return.

d. Activation and return for four electro explosive device bridge wires in two explosive bolts (eight conductors total).

The avionics interface is discussed in detail in the following sections.

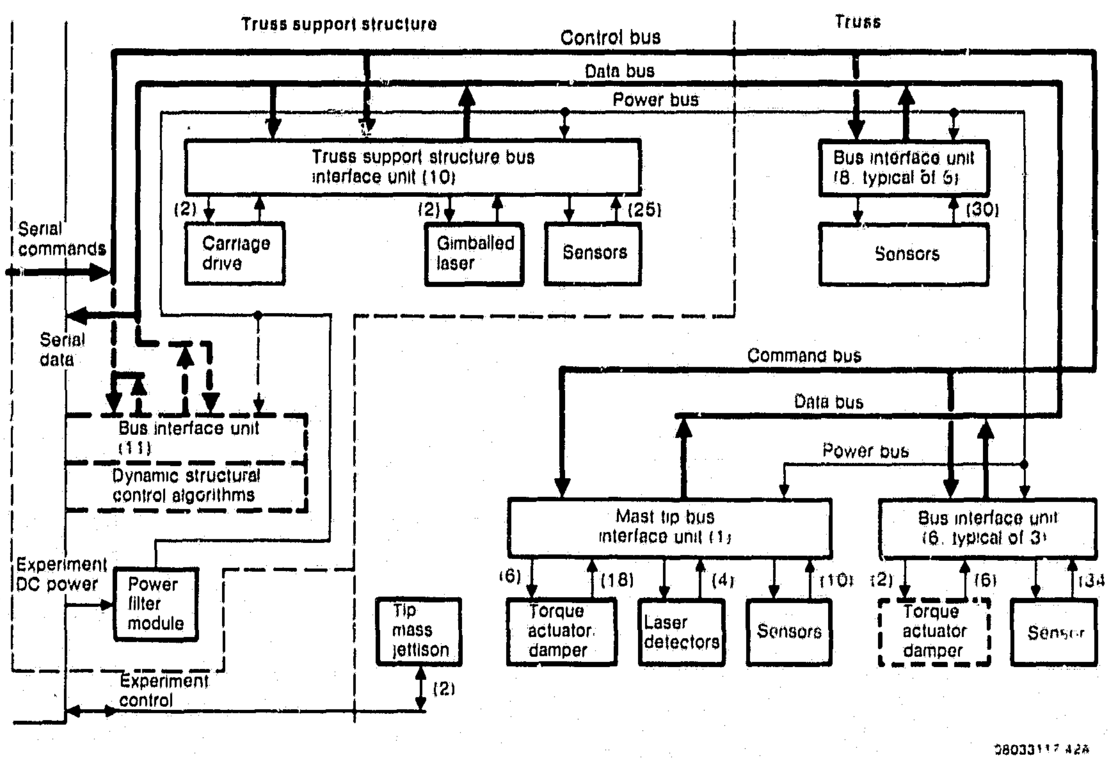

Figure 3-13. STEP/MAST Avionics Interface

3.3.4.1 Control, Data, and Power Busses. The baseline control and data bus interface is defined as:

a. Simplex serial control bus for digital commands to the bus interface units (BIU).

b. Simplex serial data bus for data transmission to the STEP experiment digital I/O.

c. 1.024 MBPS serial data rate for both control and data busses.

d. Manchester bi-phase coding for self-contained clock.

e. Sixteen bit words, 12 bit data.

f. Continuous control bus idle mode transmission (all 1's, all 0's, or alternate 1, 0) for continuous clock distribution.

g. Polling concept. Master controller is STEP data management processor. Responding units are the BIU's.

h. Variable responding message length established by BIU data storage.

The power bus implementation has:

a. A single 28 VDC power bus with remote load switching controlled by the STEP command and control processor through the BIU.

b. A power filter module for EMI rejection from the Orbiter/STEP power source, and for EMI attenuation from MAST avionics generated noise.

c. dc/dc and dc/ac power conversion within the BIU.

3.3.4.2 Bus Interface Unit (BIU). The MAST avionics has ten bus interface units for sensor/actuator interfacing with the control, data, and power busses. Characteristics common to all BIU's include:

a. Incorporate intelligence by utilizing μP technology for sensor data collection and control, and data transmission.

b. Self contained storage of all current data words.

c. Transmission of all stored data words upon receipt of transmit command.

d. No transmitter/receiver failure shall result in a control/data bus failure.

e. Continuous faulty transmitter broadcast failure shall be removable from system by power turn-off, or prevented by design.

f. Idle mode power operation for acting on incoming power turn-on control word.

g. Programmable gain for sensor groupings.

h. Twelve bit analog-to-digital sensor signal conversion.

i. Flexible provisions for adding sensors, torque actuator/damper, and dynamic structural control.

3.3.4.3 Control and Data Bus Implementation. The baseline bus implementation has a simplex control bus and a simplex data bus. Alternate implementations are feasible. Table 3-1 offers a comparison of three techniques for bus system implementation. Other techniques include loop bus, bisync, SDLC, IMUX, ETHERNET, etc. The selected bus system has to accommodate not only MAST, but other STEP experiments. The bus system possibly may have features such as:

a. A one or more MBPS bit rate compatible with the bus cable and cable length.

b. A single combined control and data bus with continuous broadcasting faulty transmitter avoided by transmitter circuit and/or logic design.

c. A token bus implementation for good flexibility at low overhead.

d. The addressed unit interprets the message, eliminating the requirement for a separate control or data word identification (ala 1553B).

e. A time gap for word synchronization eliminating the 1½ bit wide circuitry of 1553B.

f. Error detection with a parity bit.

g. An ARQ capability if desired by BIU/STEP software.

h. Flexibility with programmable word format as determined by BIU/STEP software.

i. Self clocking data with low accuracy clock generators.

Perhaps the STEP Data Management Processor would have a separate μP implemented bus controller for each experiment bus(ses), so the format (address length, status, message types, etc.) could be optimized for each experiment through BIU/Bus Controller software.

The MAST experiment will operate with the STEP designated bus implementation. If there is flexibility in the bus format, the MAST experiment design will select a format, within the STEP constraints, for optimizing MAST BIU design.

Table 3-1. Bus System Implementation Comparison

Bus System Implementation	Advantages	Disadvantages	Comments
Baseline. Simplex control bus. Simplex data bus. Polling operation.	1. No identification and overhead required to distinguish between control and data words. 2. No contention with STEP data mgmt processor doing polling. 3. Simple BIU polling response. 4. A faulty broadcasting transmitter on the data bus can be turned off over the control bus. 5. The control bus can provide clock distribution.	1. Requires two physical busses on truss. 2. Simple polling response offers little adaptive data flexibility (not important for MAST experiment). 3. Redundancy would require two more busses (non-redundant MAST ground rule).	1. Adaptive data flexibility can be improved by polling for BIU message flags, or by using time slots for message flags. This would increase the overhead. It is not required for the MAST exp. 2. Parity bit can be easily implemented. 3. Time gap can be used for word sync. Less positive than 1½ bit wide 1553B sync.
Half duplex. Combined control & data bus. Basically a polling operation.	1. Requires one physical bus on the truss. 2. Mode commands and service request flags are provided by MIL-STD-1553B for operating flexibility. Not required for the MAST experiment. 3. Parity bit provides error detection. 4. No contention during polling.	1. Requires identification of control and data words. 17% overhead for MIL-STD-1553B, also used for word sync. 2. Status words of MIL-STD-1553B adds overhead. Not required for MAST experiment. 3. Redundancy would require another bus. 4. A means has to be provided for preventing faulty transmitter broadcasting.	1. MIL-STD-1553B is most common military implementation of a half duplex bus. 2. Format could be modified to simplify BIU operation.
Half duplex daisy chain. Combined control & data bus. Basically a token bus.	1. Requires one physical bus on the truss. 2. Mode commands and service request flags are provided by proposed MIL-STD-1765 for operating flexibility. Not required for the MAST experiment. 3. Parity bit provides error detection. 4. No identification of control and data word required. The addressed receiving unit interprets the message. 5. Token passing avoids contention.	1. Word sync like 1553B does not have dual use for control and data word identification. 2. Same format as 1553B adds overhead (status). Not required for MAST experiment. 3. Redundancy would require closing the loop(another bus). 4. A means has to be provided for preventing faulty transmitter broadcasting.	1. Convair DISMUX (proposed MIL-STD-1765) is a military version which uses the 1553B format. 2. The TOKEN/NET is a commercial version of the IEEE 802 token bus operating at 5 MBPS. 3. Format could be modified to simplify BIU operation.

A large number of baseband techniques are available. Table 3-2 compares baseband techniques as regards to bandwidth required (with 1 MBPS bit rate), high frequency components magnitude (RFI generation), and the carrier frequency power level for an alternating 1-0 pattern.

The Level Shift-Amplitude Modulation (LS-AM) and Bi-Phase Carrier (Manchester Bi-Phase) had the lowest RFI generation. In Table 3-3, these two modulation techniques are compared in data from the same referenced report.

The LS-AM has a 6 db advantage over Manchester Bi-Phase. In the referenced report, the LS-AM was selected over Bi-Phase Carrier for lower generated RFI noise, reduced phase sensitivity, and simpler circuitry. The LS-AM had adequate S/N ratio for the application. Bi-Phase Carrier would be selected for a very noisy environment, since it has improved S/N performance over LS-AM.

3.3.4.4 Data and Power Bus Cables. A number of options are available for the data bus cable implementation as listed below. Table 3-4 gives a qualitative comparison of these options.

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Table 3-2. Point Spectrum Comparison at 2.5 MHz

Baseband Modulation Techniques	Power Normalized 1 ohm	Total Broadcast Power($x10^{-3}$)
Nonreturn to zero level, NRZL (2.5 MHZ)	0.065W	20W
Return to zero, RZ (3 MHZ)	0.180W	10W
Bi-Polar return to zero (2.5 MHZ)	0.045W	5W
Pulse Duration Modulation, PDM (2.5 MHZ)	0.090W	17.5W
Pulse Amplitude Modulation, PAM (2.5 MHZ)	0.180W	10W
Level Shift Amplitude Modulation, LS-AM (2.5 MHZ)	0.0037W	12.5W
Bi-Phase digital (3 MHZ)	0.180W	20W
Bi-Phase carrier (2.5 MHZ)	0.148W	5W

"S-3A Avionics Integrated Data Subsystem Trade-off Study - RF Carrier Versus Baseband," S. Maki, H. Tracy, J. Walker, GD/Convair Report No. 21-00375, 14 May 1969.

Table 3-3. Amplitude Comparison - High Frequency Component Vs. Original Signal Level

Component Frequency	Bi-Phase DB Difference	Level Shift DB Difference
1/2T	-1.4 db	-7.4 db
3/2T	-2.3 db	-8.3 db
5/2T	-10.4 db	-16.4 db
7/2T	-14.1 db	-20.1 db

Table 3-4. Characteristics Comparison of Signal-Transmission Cables

Characteristics	Cabled Twisted Pairs	Coaxial Cable Solid Core	Coaxial Cable Air-Spaced	Tri-Lead	Flat Cable	Fiber Optics
Impedance Tolerance	P	E	E	G	E	-
Attenuation	F	E	E	G	G	E
Crosstalk	G	E	E	G	F-G	E
Time Delay	P-F	G	E	G	G	P
Rise Time	F	G	E	G	G	E
Bandwidth	F	G	E	G	F	E
Mechanical Integrity	E	G	G	F	F	G
Flexibility	G	G	G	E	E	E
Cable Dimensions	P	E	E	G	G	E
Dimension Tolerance	F	G	G	G	E	E
Cable Cost	E	G	G	F	F	G
Installed Cost	F	F	F	F	E	P

NOTES: E = Excellent, G = Good, F = Poor

Data bus cable

- Twisted, shielded, jacketed pair.

  Standard in most low frequency installations (up to 10 MBPS).

- Twin and tri-lead.

  Little shielding available.

- Coax

  Typically for higher frequency signals.

- Four layer flex.

  Wider outer layers for shielding.
  More flexible, performance not known.

- Fiber optics.

  Very flexible.
  Excellent ground isolation.
  No known space application to date.
  Terminations not standardized.
  Very high frequency potential.

Further MAST design studies will evalute the suitability of TSP cable. If it proves to be unsatisfactory (not anticipated) for the MAST experiment, then flex cable and fiber optics will be considered.

The power bus cable will be either standard power conductors or a multi-conductor flex cable. Standard power conductors will be evaluated for suitability during MAST design.

3.3.5 MAST AVIONICS. The MAST avionics for Configuration I consists of (Figure 3-13):

a. The ten BIU's for sensor/actuator interfacing.

b. A MAST tip torque actuator/damper for MAST experiments.

c. Truss structure mounted sensors (thermocouples, strain gauges, accelerometers) for assessing structure performance, and experiment feedback.

d. Dual rail carriage deployment/retraction redundant drive.

e. Laser tracker (GFE) for tip deflection and tip longitudinal motion sensing.

f. Power filter module to suppress STEP/Orbiter generated transients and prevent MAST generated EMI.

g. Hardware control of redundant tip mass jettison pyro bridge wires.

h. Control, data, and power busses.

i. Expansion flexibility for adding three torque actuator/damper sets and dynamic structural control algorithms for MAST Configuration Ia, and additional undefined avionics for Configurations II and III.

3.3.5.1 Bus Interface Unit (BIU). The BIU located at truss bay number 5 (Figure 3-14) is typical of five BIU's that interface only with truss structural sensors. Interfaces for this BIU are the control, data, and power busses; and structural sensors consisting of six thermocouples, 24 strain gauges, and two pizeo-electric accelerometers. Microprocessor technology is utilized for formatting flexibility, gain programming flexibility, bus protocol flexibility, and expansion flexibility at low hardware cost.

The BIU will be implemented with low chip count hardware for light weight, compact packaging suitable for truss mounting, and with low cost permitting multiple unit deployment along the mast. Implementation will use MIL Standard qualified temperature range

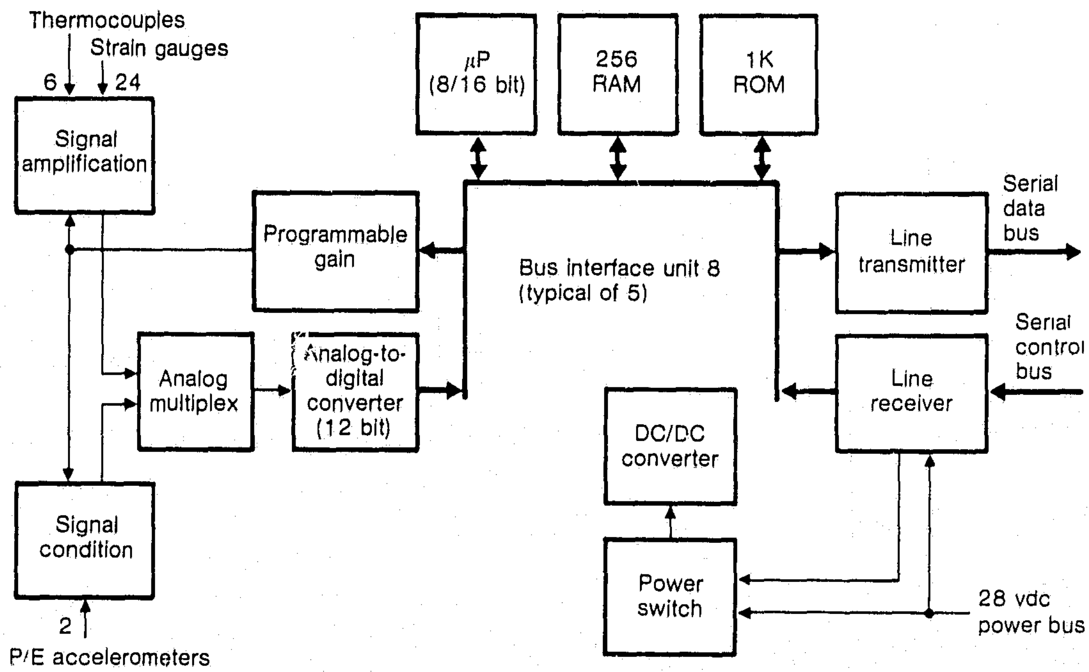

Figure 3-14. Bus Interface Unit for Truss Bay No. 5

components with high reliability processing. The elements would consist of (for the baseline bus system):

a. Single device line transmitter (examples, bus 63105 transcensor for MIL-STD-1553B, DS 1691 for MC6854 SDLC).

b. Single device line receiver (example, AM 26LS32 for MC 6854 SDLC).

c. Single unit serial-parallel, parallel-serial, validity check functions (e.g., CTI 1555 for 1553B, MC 6854 for SDLC).

d. IK ROM two chips maximum, 256 RAM two chips maximum.

e. 8/16 bit μP, typical candidates:

MIL 2901 bit slice, rad hard, bi-polar.
MIL 8X305 μ controller, rad hard, bi-polar.
MIL 9989 16 bit, rad hard I^2L
MIL Z80 8 bit, Z8002 16 bit, rad sensitive.
MIL pending 6400 8 bit, 6400 16 bit, rad sensitive.
MIL M8085 8 bit, M8086 16 bit, rad sensitive.

f. Twelve bit analog-to-digital converter (e.g., TSC 7109, MP 7521 DAC).

g. 8 bit programmable gain amplifier (e.g. MN2020).

h. Signal conditioning and analog multiplexing sized to requirements.

The BIU for the MAST tip location is shown in Figure 3-15. It interfaces with the dual 3-axis torque actuator/damper and the laser tracker detectors, in addition to the structural sensors. The additional features (shown dotted in Figure 3-15) are:

a. 1K or more added ROM for torque actuator/damper control and excitation function instructions.

b. Digital I/O for interfacing with dual 3-axis torque actuator/damper.

- Additional remote power control switch for A.C. excitation of rate sensors.

- Additional remote power control switch for activation of inertia wheel drive.

- Pulse width modulated switching for inertia wheel drives (DAC for analog drive is an alternative).

The truss support structure BIU interfaces with the laser tracker and the carriage drive, in addition to structural sensors (Figure 3-16). The added features are:

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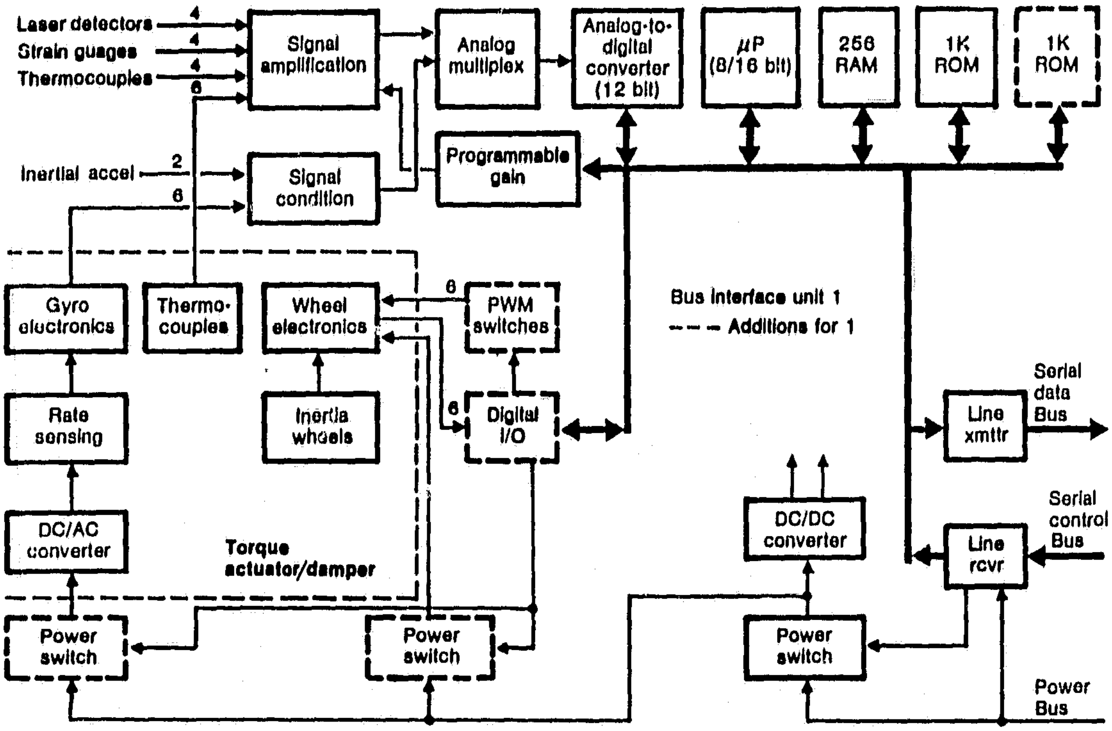


Figure 3-15. MAST Tip Bus Interface Unit

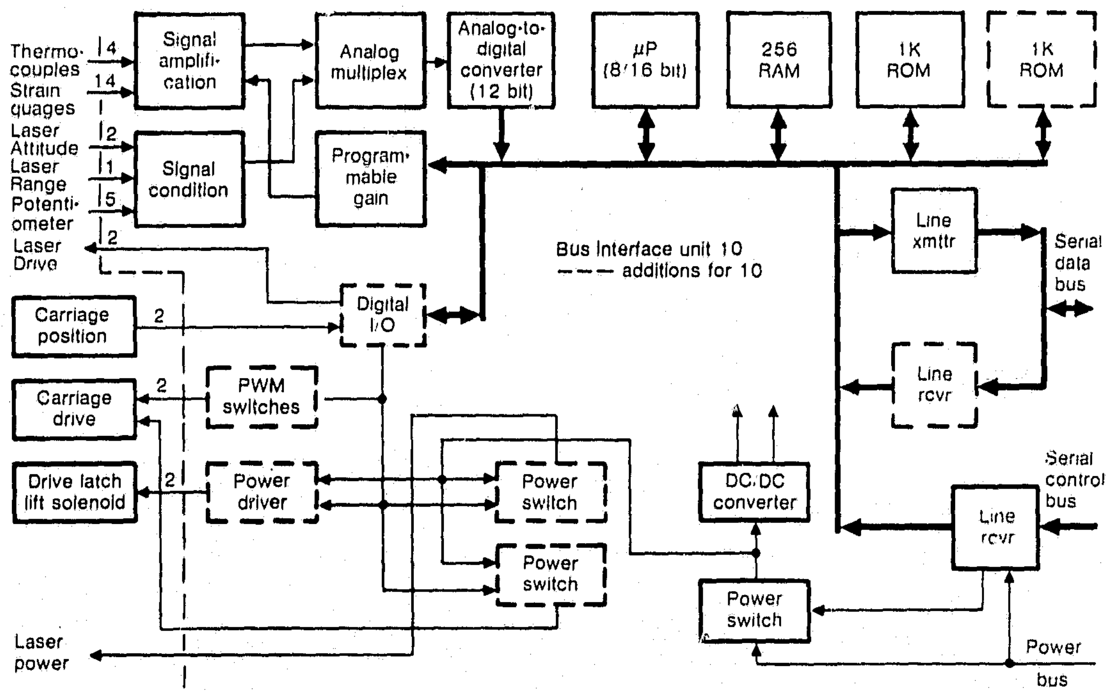


Figure 3-16. Truss Support Structure Bus Interface Unit

a. Data bus line receiver.

- Strip laser tracker detector data from MAST tip bus interface unit data stream.

b. 1K or more added ROM for carriage drive control, and laser tracker attitude control algorithm instructions.

c. Digital I/O for interfacing with laser tracker and carriage drive.

- Additional remote power control switches for laser tracker power and carriage drive power.
- Additional discrete power switches for solenoid operation.
- Pulse width modulated switching for carriage drive motors.

All the BIU's have spare sensor interface provisions. Three of the BIU's have designed-in spare interfaces for the 2-axis torque actuator/damper of mast Configuration Ia.

3.3.5.2 Carriage Drive. The carriage drive control concept is shown in Figure 3-17. The functional blocks shown within the BIU dotted interface of Figure 4-6 are provided by the BIU software.

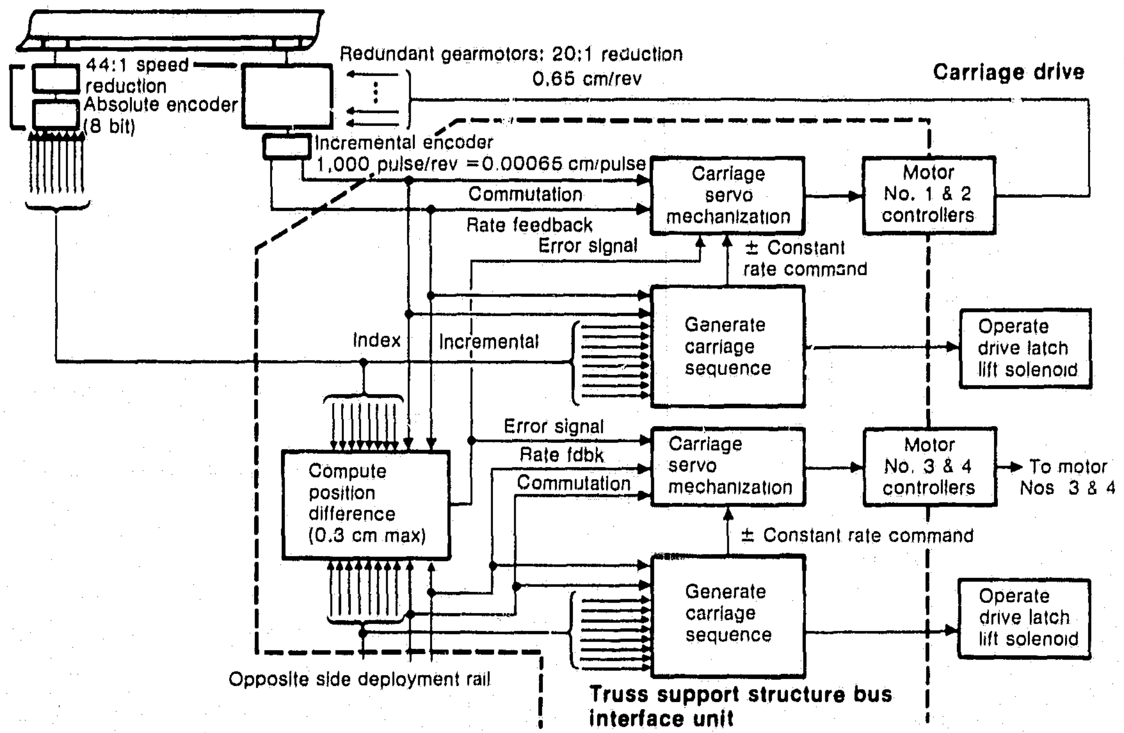


Figure 3-17. Carriage Drive Control Concept

The carriage servo control loop mechanization is contained in the unit μ processor software and appropriate input/output. The carriage sequence software generates the commanded constant rate with ramp/de-ramp rates, and the solenoid driver activate/de-energize signal in accordance with the desired deployment or retraction sequence as a function of carriage position.

The rate stabilization software differences the commanded rate and the pulse rate feedback for a rate error signal. Control filtering is provided for high stability margin servo performance. The opposite side carriage servo also sums in a position error signal with appropriate proportional lead plus integral compensation for good position tracking performance.

The pulse width modulation software generates a pulse modulated output as a function of the control error signal, to obtain a low power dissipation mode of motor operation. The stator field winding switches are sequenced by the commutation sequence software for correct winding energization by the pulse width modulated signal. The pulse width modulation software includes a time-out function so a too long, high modulation signal (representing long duration high torque) results in automatic shutdown with Mission Specialist notification. The torque switches use HEXFET devices with high gain, and a positive temperature coefficient without secondary breakdown.

Redundant carriage drive motors (two per rail, four total) are provided for high reliability truss deployment, retraction operation. Thermocouples measure motor temperatures for Mission Specialist operating information.

3.3.5.3 <u>Torque Actuator/Damper</u>. A dual 3-axis torque actuator/damper will be mounted on the MAST tip for Configuration I. For Configuration Ia, three more single 2-axis torque actuator/dampers will be added. Off-the-shelf gyro angular rate sensing and inertia wheel structure node torquing will be employed. The BIU software will provide the structural damping control loop algorithms and the structural torque excitation function as commanded by the STEP command and control processor. For inertial wheel drive, either high frequency (to avoid uncontrollable excitation of the structure) pulse width modulation motor excitation or analog motor excitation will be employed.

3.3.5.4 <u>Dynamic Motion Sensors</u>. Three types of dynamic motion sensors will be used. Angular rate sensing at structural nodes, pizeo-electric accelerometers for structural anti-node displacement high level acceleration sensing, and inertial grade accelerometers for low level anti-node sensing. Off-the-shelf units will be used.

3.3.5.5 <u>Structural Sensors</u>. Structural sensors include strain gauges in the truss support structure, and truss bays 5 and 30 for structural member loading information; thermocouples for relating to MAST deflection and longitudinal extension; trunnion pin potentiometers for relative MAST/STEP dynamic and static motion;

and a GFE supplied laser tracker for MAST tip dynamic and static deflection and longitudinal motion.

3.3.5.6 MAST Configuration Ia. For MAST Configuration Ia, a BIU is added (Figure 3-13) for the dynamic structural control algorithms. The BIU shown in Figure 3-18 has the features:

a. Sequential control bus implementation.

- BIU receives command words for MAST from STEP command and control processor.
- BIU interprets commands for internal action or for re-transmission to other MAST BIU's.
- With added line transmitter, BIU transmits commands to other BIU's.

b. Additional line receiver for BIU access to allMAST data, in particular torque actuator/damper units rate and wheel speed data.

c. Dynamic structural control implementation.

- Torque actuator/damper data, acceleration data, and structural data received for plant information.

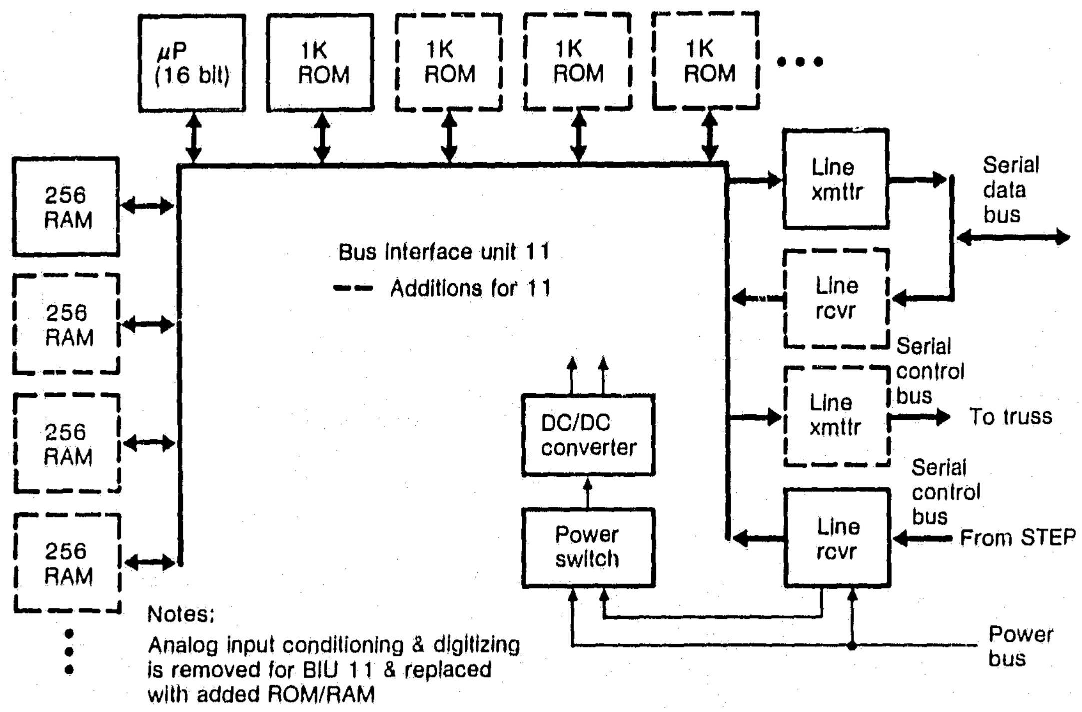


Figure 3-18. Bus Interface Unit for MAST Configuration Ia

- Dynamic structural control algorithms. Multi-K ROM and RAM added, amount dependent on control algorithm complexity. Analog signal conditioning and digitizing circuitry removed for added space.

- Torque actuator/damper control words transmitted on truss control bus.

3.3.6 MAST CONTROLS SUMMARY. In summary, the features of the proposed MAST controls are:

STEP master control and data processing

- Mission specialist supervisory control with AFD keyboard and display unit.

- STEP data management processor performs MAST data processing, formatting, storage, retrieval and transmission.

Simple STEP/MAST Electronic Interfaces

- Serial control bus for STEP command and control processor.

- Serial data bus to STEP data management processor.

- Power bus.

- Safety hardwires.

Localized actuator control and sensor data acquisition

- Intelligent bus interface units provide control loops operations and sensor data digitizing.

- Detail carriage drive sequencing performed by a bus interface unit.

Remote power bus switching

- Prime 28 VDC power bus controlled from AFD SSP.

- Remote load power switching under STEP command and control processor operation.

System safety

- Carriage retract capability with drive redundancy.

- Remote power switching.

- Hardware tip mass jettison by experiment switch panel.

- MAST jettison capability with Orbiter RMS.

3.3.7 MAST CONTROLS RECOMMENDATIONS. It is recommended that investigations be conducted to assess the suitability of standard TSP cable for the serial digital busses, and standard power conductors for the power bus. Methods of cable and avionics mounting need to be assessed. Information interchange has to continue on the STEP/MAST control/data bus protocol, formats, timing, signal amplitudes, etc. Information transfer is required on the GFE laser tracker. Preliminary design of the Bus Interface Unit, Torque Actuator/Damper, and Carriage Drive can progress.

3.4 DESIGN ANALYSIS

Analyses were performed to verify the structural capability of the revised SCE truss and truss support structures. Mass properties were also updated to incorporate the latest configuration data.

3.4.1 STRUCTURAL ANALYSIS. Truss loads for the revised truss configuration (see Figure 3-3) with a 100 Kg tip mass and VRCS control moments applied by the Orbiter were determined to be very low, as seen in Figure 3-19. The truss struts are manufactured from GY70/934 graphite epoxy material and are 0.5 inch in diameter with an 0.060 inch wall. Further refinement of the structure would be required to ensure that the experiment requirements are satisfied with a minimum weight, minimum cost design with an optimal compaction ratio.

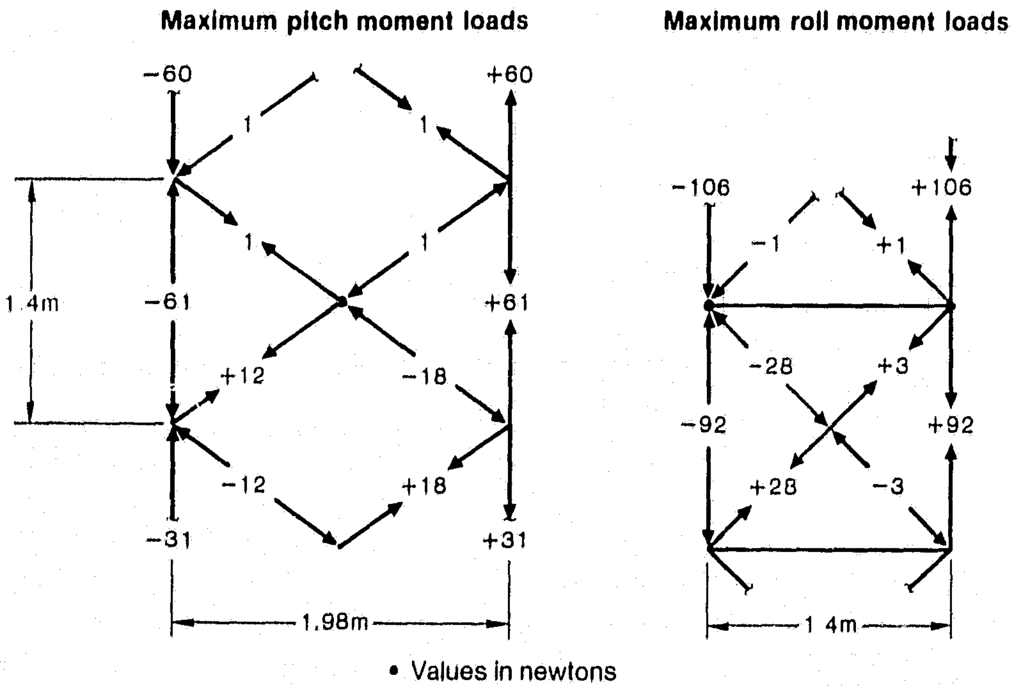
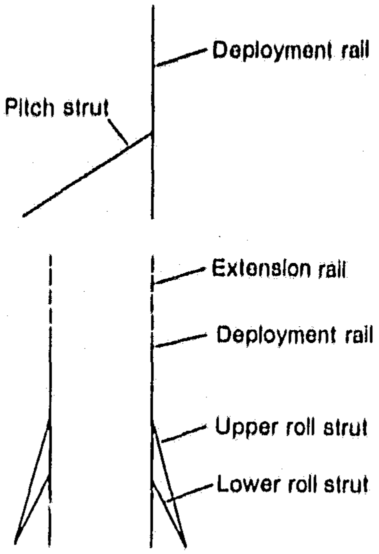


Figure 3-19. Revised Truss Loads

Deployment rail loads were computed for the new deployable truss configuration with a 100 Kg tip mass. Shear and moment loads applied in pitch and roll were determined for the VRCS "on" case. The maximum loads are summarized in Figure 3-20.

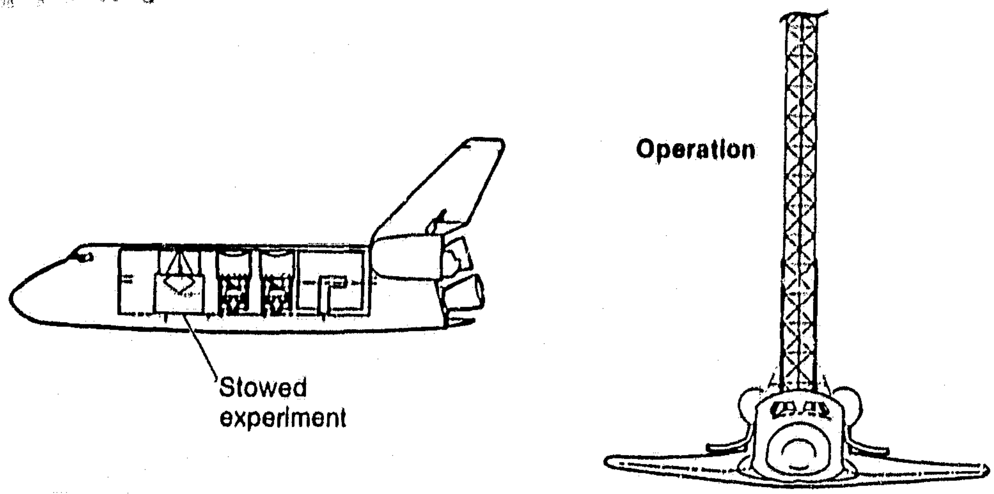


Support Structure Element	Loads	Value
Upper roll strut	Axial	75N
Lower roll strut	Axial	2N
Pitch strut	Axial	42N
Deployment rail	Axial	37N
Deployment rail	Shear	22N
Deployment rail	Moment	2 N·m

Truss stiffness (EI)
Pitch — 1.69×10^7 Nm^2
Roll — 0.83×10^7 Nm^2

Figure 3-20. Maximum Truss Support Loads

3.4.2 MASS PROPERTIES. Mass properties for the revised experiment were calculated, see Figure 3-21. The moments of inertia are given relative to the center of mass of the experiment. The center of gravity is shown relative to the Orbiter coordinates. The mass properties of the Orbiter are not included in these tables. The center of gravity for the fully deployed truss with the tip mass ejected is shown for reference.



Item	Weight (kg)
Tip-mass	100
Truss	154
Cradle	322
Experiments	43
Total	629

Deployed Phase	Center of Mass (m)			Moment of Inertia (kgm^2)		
	X	Y	Z	I_{xx} (Roll)	I_{yy} (Pitch)	I_{zz} (Yaw)
1/2	17.42	0	17.40	8.04×10^4	8.04×10^4	4.2×10^2
Full	17.42	0	29.39	3.53×10^5	3.52×10^5	4.2×10^2
Jettison tip-mass	17.42	0	20.39	1.47×10^5	1.47×10^5	4.1×10^2

Figure 3-21. Mass Properties

SECTION 4

DYNAMICS AND INSTRUMENTATION ANALYSIS

One of the objectives during part II of the study was to design an experiment that would explore the proven limits of the Orbiters Digital Autopilot (DAP). This requirement was dropped during part III. Due to the time delay involved with preparing and transmitting the data, the results were not available at the conclusion of Part II consequently they are presented herein.

The structural dynamics characteristics of the experimental structure developed during Part III of the study and the instrumentation to measure their behavior are also covered in this section. It should be noted that there are several areas that are different from the usual structural test. First, the modal frequencies are lower than those encountered in past testing, second is the use of torque rather than force for excitation which is dictated by the low frequencies, and third is the fact that while the structure has some of the characteristics of a cantilevered beam there are deviations from that behavior.

4.1 DIGITAL AUTOPILOT/STRUCTURE INTERACTIONS

The intent of this activity is not to evaluate possible DAP instability in flight but rather to operate outside of comfortable limits to the point where performance degradation did occur. This would provide data to evaluate the ability of computer simulations to predict the off nominal performance which would, in turn, add confidence in the ability of the simulations to accurately predict the performance of the DAP with large flexible structure deployed from the payload bay.

The DAP simulations were run at the Charles Stark Draper Laboratory (CSDL) using structural dynamics data supplied by GDC. In Part I of the study it was determined that the DAP rate estimator acts as a heavy bending filter with a 0.04 Hertz corner frequency. In an attempt to reach structural frequencies which would pass the filter, a soft mount was designed for the experimental structure. This soft mount could be locked out so as to provide nominal mounting stiffness. Also, the soft mount concept provided the capability to change the mounting stiffness (and thus the first mode frequency).

The data used by CSDL for the simulation results presented herein is shown in Figure 4-1. It should be noted that the data is for a 100 meter structure as used in Part II of the study. Due to the time delay involved with preparing and transmitting the data, the results were not available at the conclusion of Part II. Since the requirement to experimentally evaluate DAP interactions was dropped during Part III, simulations were not run for the current 60 meter structure. In addition, the soft mount has been eliminated.

Mode	Description	Frequencies (Hz)			
1	1st pitch bend	.0390	.0861	.0391	.1192
2	1st roll bend	.0618	.1138	.0533	.1322
3	2nd roll bend	.6716	.9350	.6677	.9586
4	2nd pitch bend	.8069	1.1783	.8116	1.2092
5	3rd roll bend	2.2826	2.8937	2.2678	2.9298
6	1st torsion	2.7943	3.1956	2.7901	3.1956

Tip mass (kg)	250	250	100	100
Support stiffness (n/m)	1.55×10^5	∞	$.75 \times 10^5$	∞

Truss characteristics	
EI pitch	2.0×10^7 N-m^2
EI roll	1.3×10^7 N-m^2
Length	100m
ℓ	2.0m
h	2.83m

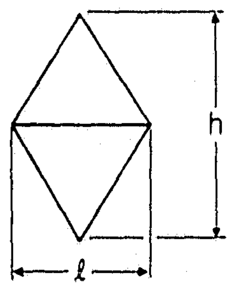


Figure 4-1. Structural Dynamic Characterists for DAP Interaction.

The CSDL simulation runs consisted of making a 5 degree attitude change in pitch or roll with rate limits of 0.02 deg/sec and deadbands of 1.0 degree. Sixty seconds into the run the rate limits are tightened to 0.01 deg/sec and the deadbands to 0.1 degree. A total of eight runs were made, four each, in pitch and roll. The four different cases consist of combinations of a 100 Kg or 250 Kg tip mass and soft or nominal mount.

When inspecting the computer simulation results it is necessary to remember that the DAP is a nonlinear system. Thus, behavior which appears to be divergent may or may not continue to diverge and the response will be strongly influenced by the particular initial conditions present when the limits are tightened.

Figures 4-2 and 4-3 show what was expected to be worst cases since the soft mount has given a first bending frequency of about 0.04 Hertz. The traces show only the bending mode reponse and not the rigid body response. The pitch acceleration trace has been included in the figures since it best shows thruster firings. The expected worst cases are relatively benign which indicates that more than a simple frequency criteria is needed to predict adverse interactions. When the nominal mount is used to raise the frequencies, the results in terms of extraneous thruster firings is much the same as before with no significant adverse interaction exhibited.

In the roll axis, see Figures 4-4 and 4-5, the results are quite different than those for the pitch axis with what may be divergences and excessive thruster firings even before the rate limits and deadbands are tightened. Since case by case the roll bending frequencies are higher than for pitch, it is again indicated that frequency may be only part of the story. The other significant difference between the two axes is moment of inertia. Since the roll moment of inertia of the Orbiter is much smaller than that of the pitch axis, oscillations of the structure would be expected to have a greater effect in causing motion of the Orbiter. The DAP is a complex system and many more runs of greater length would be required to define the adverse interaction envelope, but it does appear that the envelope is a function of both moment of inertia and frequency.

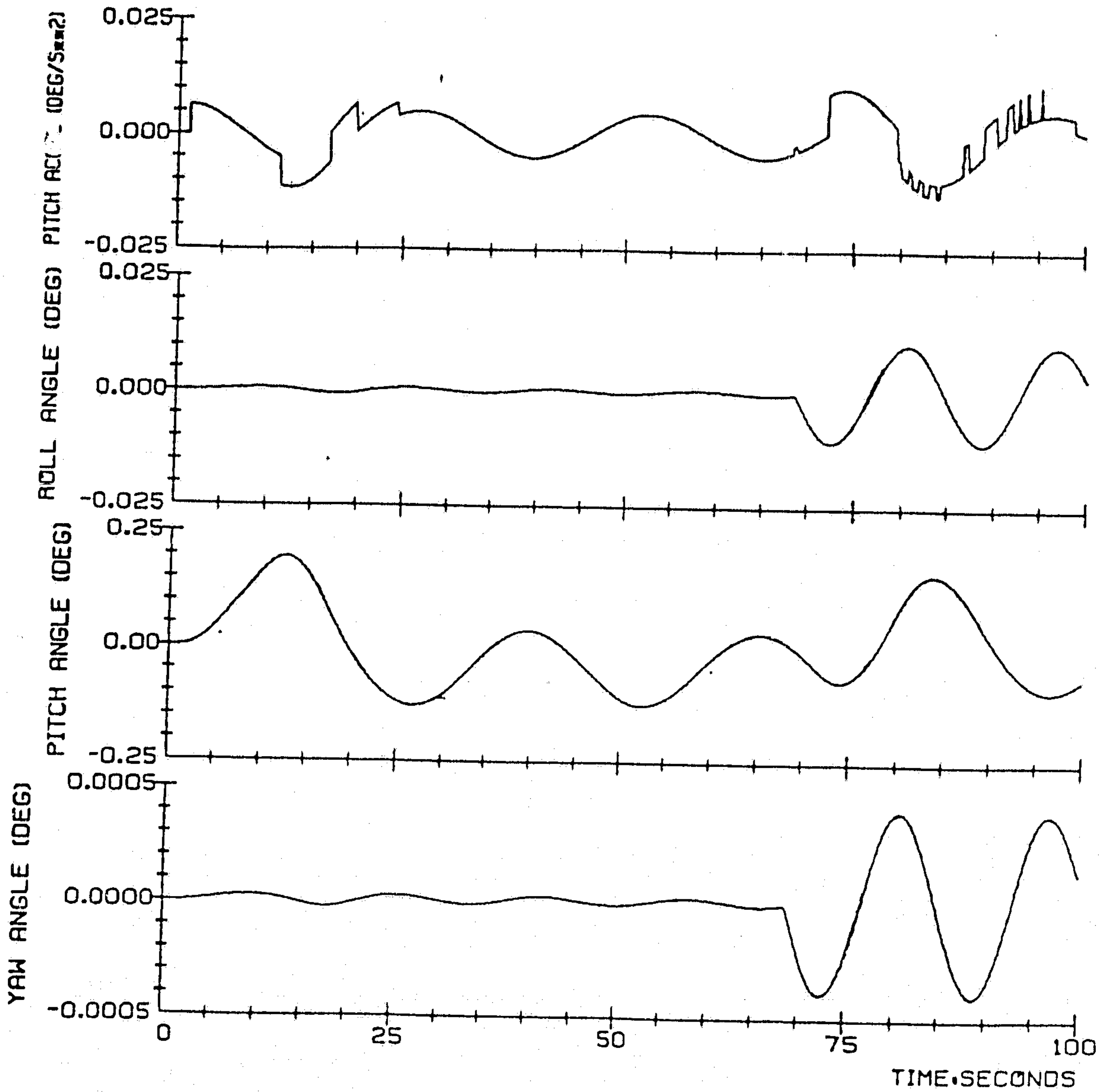


Figure 4-2. DAP Interaction with 100 Kg Tip Mass and Soft Mount, Pitch Axis.

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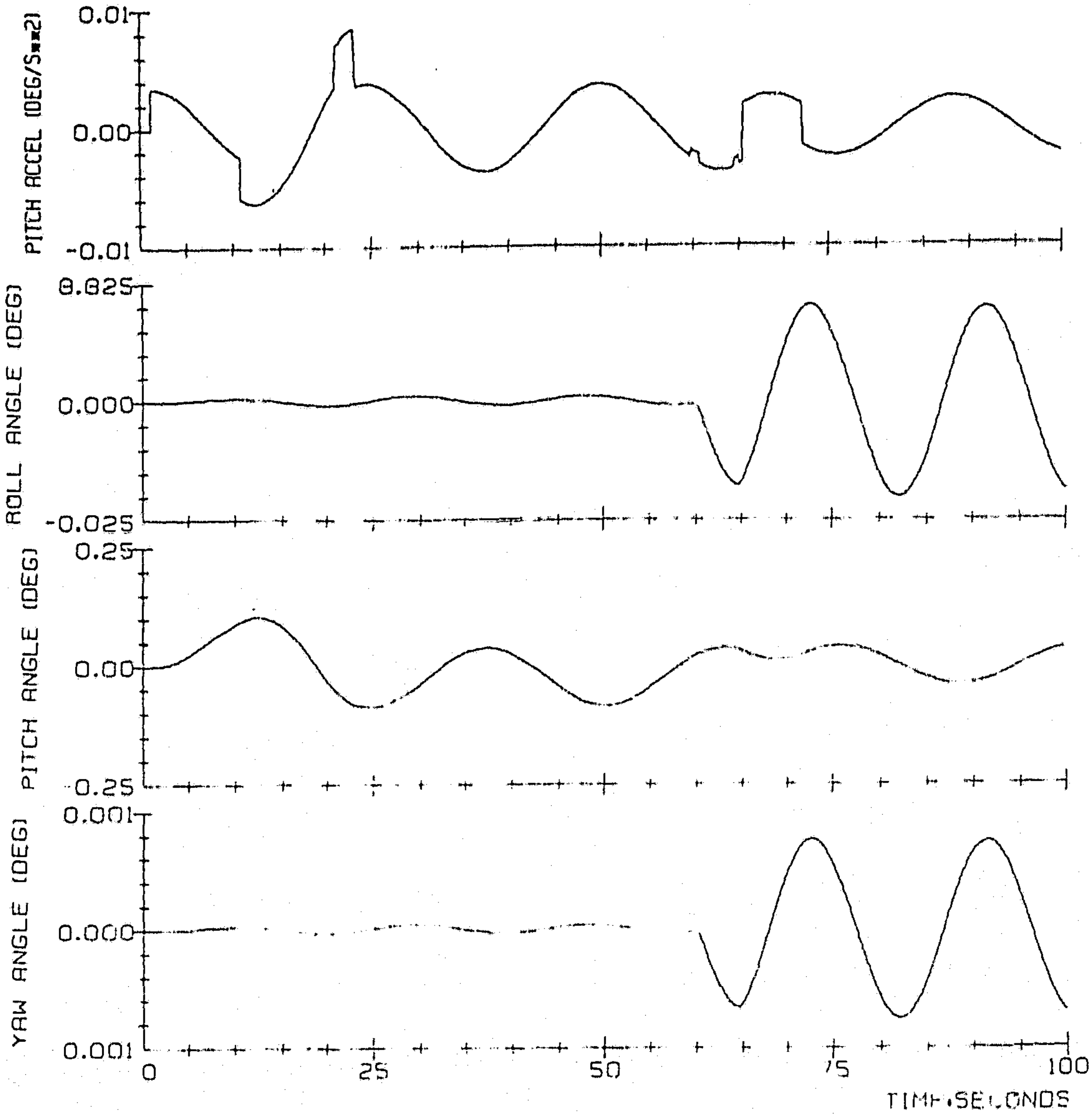

Figure 4-3. DAP Interaction With 250 Kg Tip Mass and Soft Mount, Pitch Axis.

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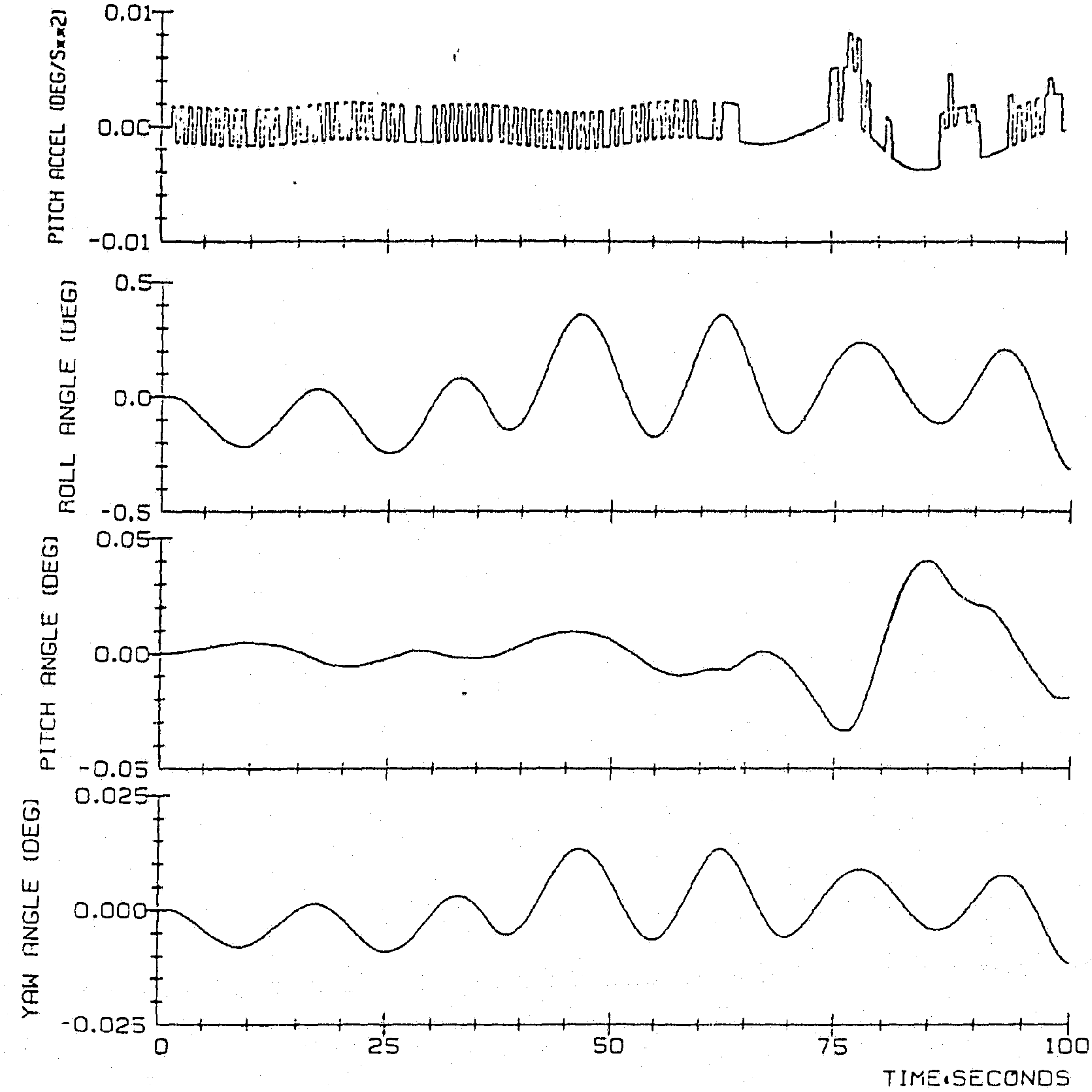


Figure 4-4. DAP Interaction With 100 Kg Tip Mass, Roll Axis.

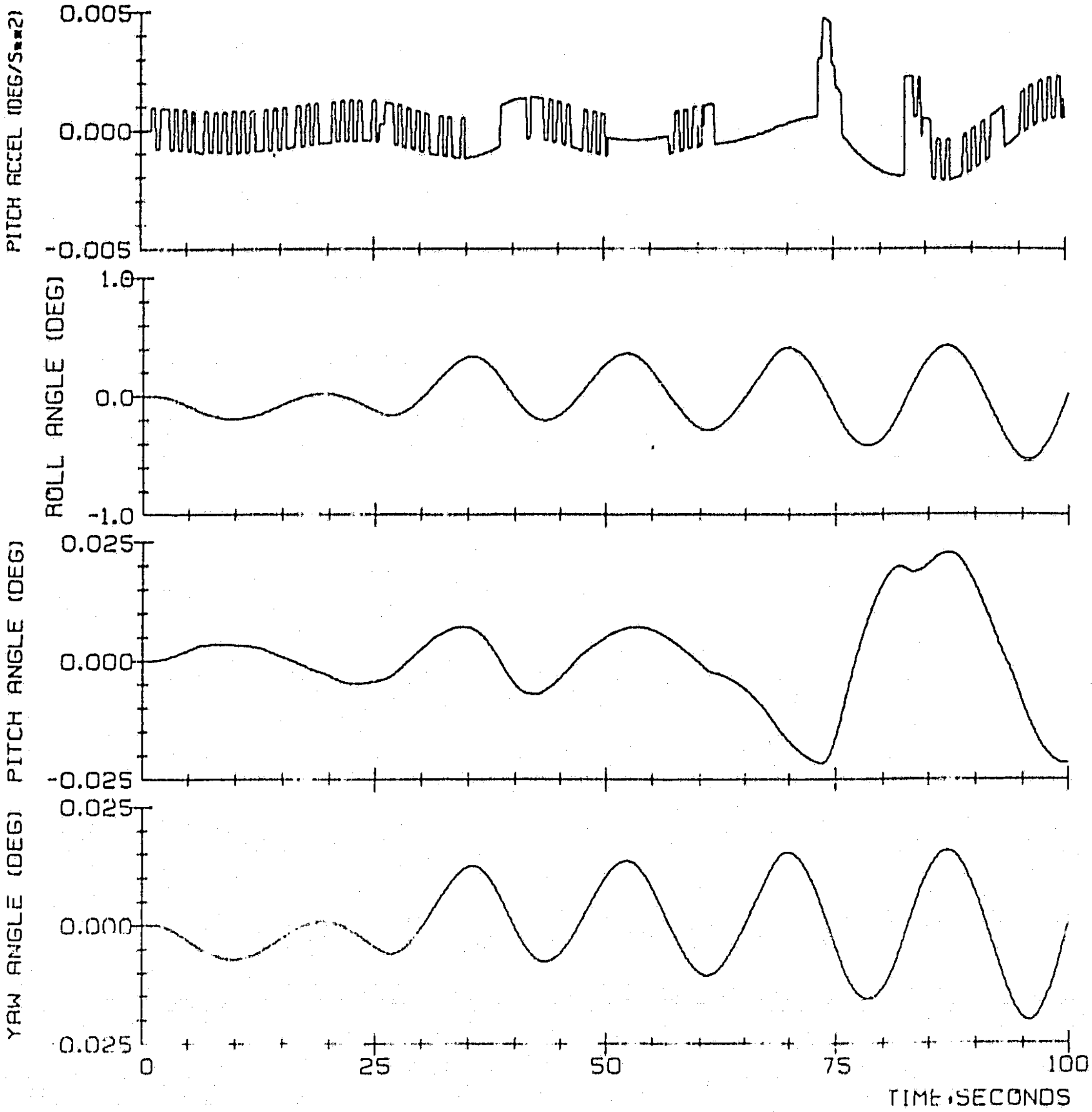


Figure 4-5. DAP Interaction With 250 Kg Tip Mass and Soft Mount, Roll Axis.

4.2 FLEXIBLE MODE SUMMARY

The modes of interest are the first five modes in pitch, the first five modes in roll, and any other modes that fall in the frequency band set by the pitch and roll modes. The modes of interest are shown in Table 4-1 and it can be seen that the frequency ranges from 0.190 Hertz for the first roll bending mode to 26.5 Hertz for the fifth pitch bending mode. There are two compression modes and one torsion mode in the frequency band of interest. It might be noted that the first bending mode is above 0.15 Hertz which has been set as the lower allowable limit to avoid adverse coupling with the Digital Autopilot of the Orbiter. In both pitch and roll, the second bending mode is at least an order of magnitude greater in frequency than the first mode. This does not correspond to a cantilevered beam with uniform mass distribution, but has been encountered before in beams with tip masses.

Table 4-1. FLEXIBLE MODE SUMMARY

Flexible Mode No.	Frequency Hz	Axis			
		Pitch	Roll	Torsion	Compression
1	0.190		✓		
2	0.238	✓			
3	1.91		✓		
4	2.71	✓			
5	5.98		✓		
6	8.47	✓			
7	10.46				✓
8	10.68			✓	
9	12.16		✓		
10	17.18	✓			
11	17.34		✓		
12	18.40				✓
13	21.0		✓		
14	26.5	✓			

Figure 4-6 shows the mode shapes for the first five pitch bending modes. As might be expected, the shapes correspond to those of a simple cantilevered beam: the first mode has one node, the second mode has two nodes, and so on. It should be noted that the support structure compliance must be considered in modes three and higher. This is especially apparent in the fourth mode where there is appreciable deformation of the support structure. Of course the amplitude shown causes no problem with the computer model and the associated graphics, but the amplitude indicated would not be encountered during a flight experiment.

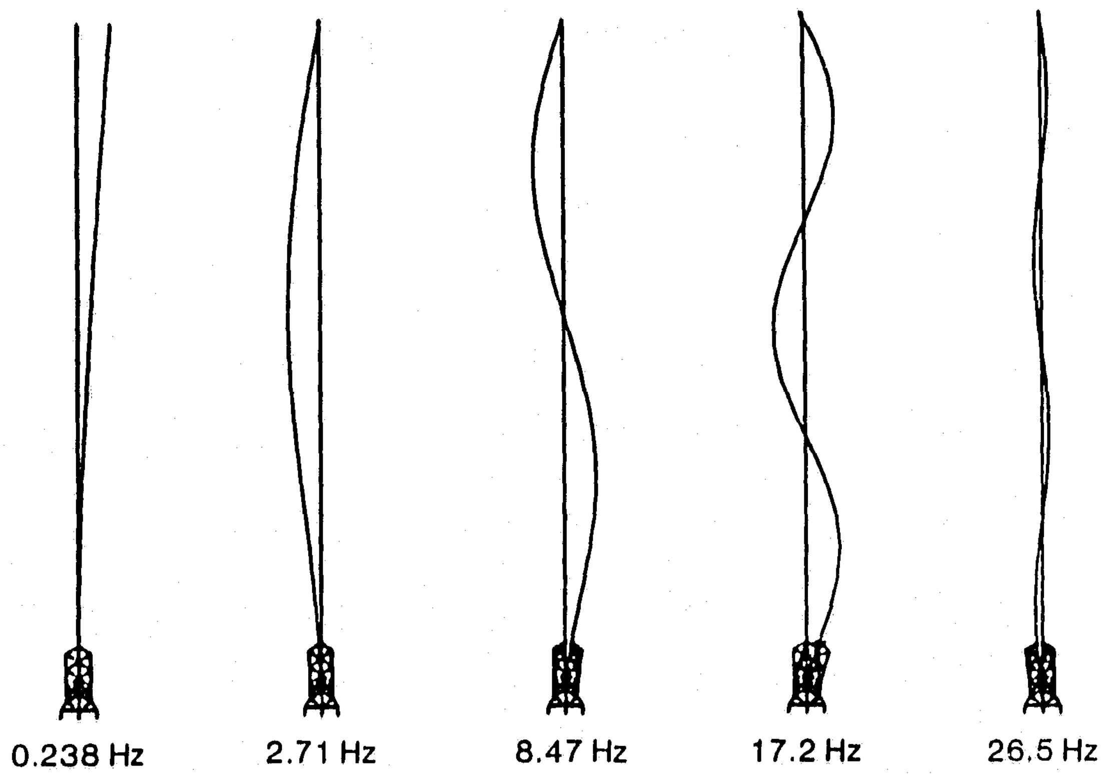


Figure 4-6. Pitch Bending Mode Shapes

The roll bending modes are shown in Figure 4-7. They appear much the same as the pitch modes although the support structure compliance does not appear until the fourth mode. Although it cannot be seen in the Figure, the small roll moment of inertia of the Orbiter influences the modes in roll much more than the Pitch inertia influences the pitch modes. These are free-free modes and do differ from what would be calculated for true cantilever modes.

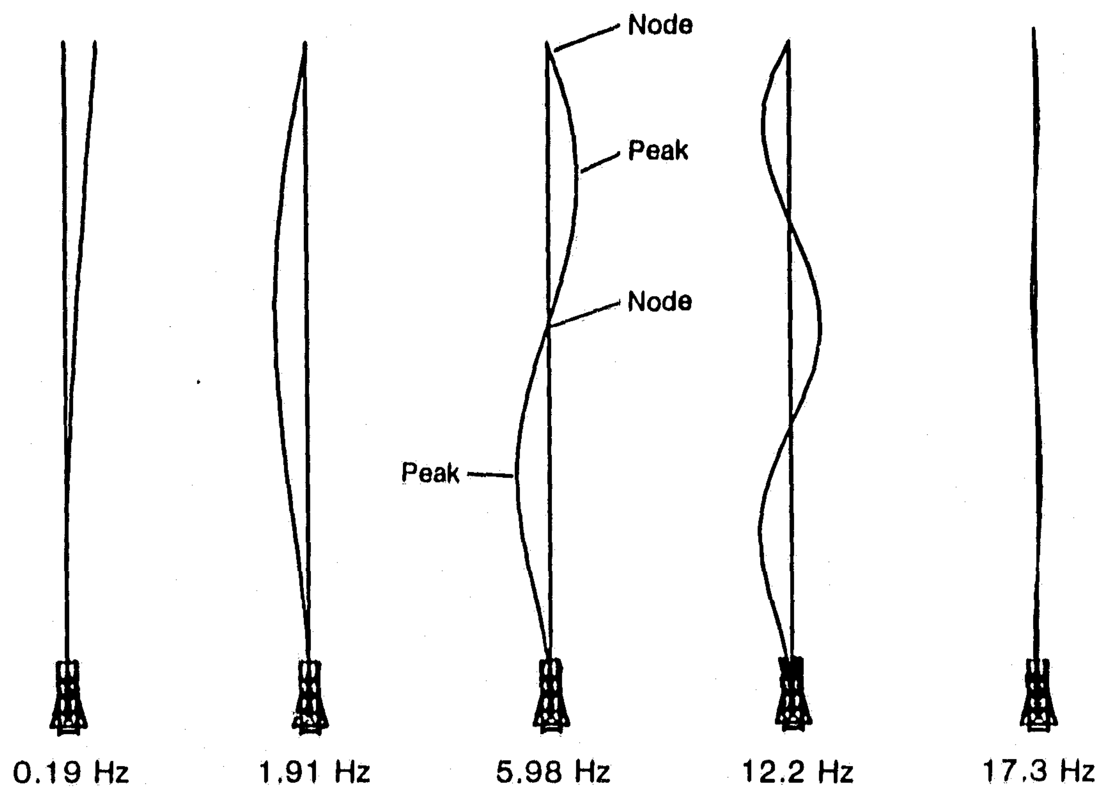
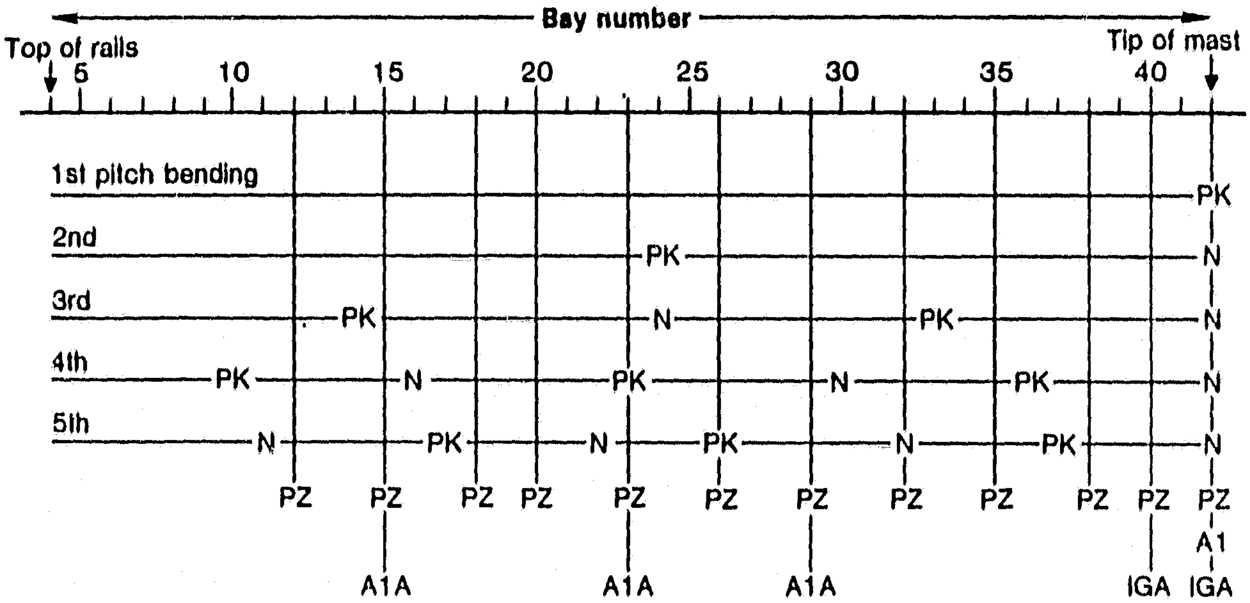


Figure 4-7. Roll Bending Mode Shapes

4.3 INSTRUMENTATION LOCATION

The third mode peaks and nodes have been identified in Figure 4-7. Structural testing has historically dealt with force inputs and linear (acceleration) measurements. Both the force application and the linear measurement are most effective at mode shape peaks and totally ineffective at nodes. Because force actuators have practical problems at low frequencies, the flight experiment uses torque actuators which, in turn, require slope or angular information for closed loop operation. When working with torques and slopes the situation is reversed from the force case: torques and slope sensors are most effective at nodes and ineffective at peaks.

Figure 4-8 presents a graphical presentation of the experimental structure wherein the horizontal axis at the top of the chart indicates bay location along the structure with 42 being the tip and 4 being the top of the deployment rails. Peaks and nodes



PK = Mode shape peak
N = Mode shape node

PZ = Accelerometer location
A1 = Config 1 actuator location
A1A = Higher config actuator location
IGA = Inertial grade accelerometer

Figure 4-8. Dynamics & Control Components Location, Pitch Axis

are indicated for the first five pitch bending modes and sensor and actuator locations are indicated. Since the maximum slope for all modes shown is at the tip, the tip actuators can excite all of the modes. For configuration 1A and higher, there is an actuator close to at least one additional node for the third mode and above. The accelerometers are generally within one bay of the peaks and the important nodes have two accelerometers close by. Two measurements near a node permit interpolation or extrapolation to more accurately determine the exact location of the node. Two inertial grade accelerometers are used, principally for the first mode which, by virtue of its low frequency, will have significantly lower accelerations than the higher modes.

Figure 4-9 shows the layout for the roll axis. Installation of the instruments and actuators is such that both roll and pitch components should be located at the same bay so as to avoid excessive repetition of the special modifications required to mount the components on the structure. Inspection of the Figures will show that locating the components for the roll axis at the same locations as used for pitch gives excellent coverage for both axes.

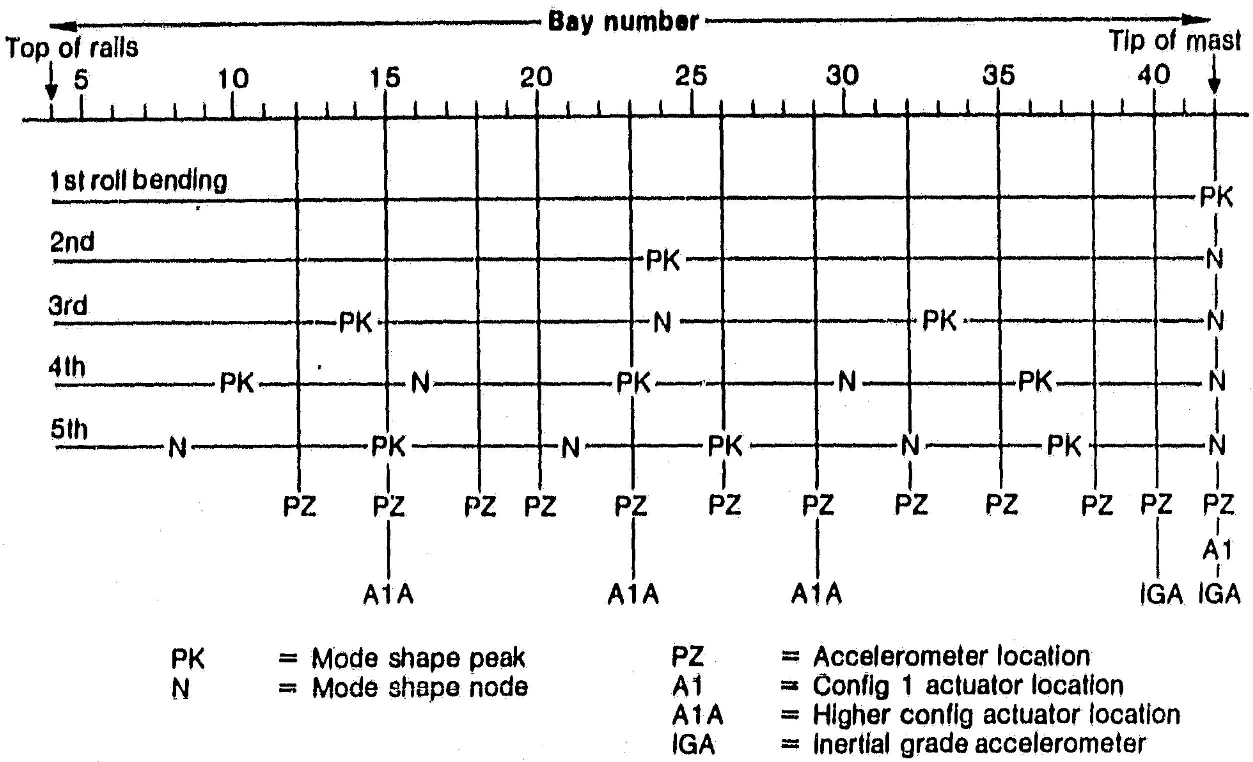


Figure 4-9. Dynamics & Control Components Location, Roll Axis

In addition to the instrumentation for the modes of the experimental structure, instrumentation has also been provided monitoring the structure and the deployment mechanism. Table 4-2 summarizes all of the instrumentation. In addition to that already discussed, provision has been made for monitoring loads into the Orbiter, structural loads and temperatures, tip location relative to the base, deployment carriage position, and actuator motor temperatures.

Table 4-2. Flight Instrumentation Summary

No.	Measurement	Type Sensor	Qty	Location
1	Tip motion rate	Rate gyro	6	1 each damper set
2	Mode shape & frequency	Servo-accelerometer	4	2 each at 2 truss stations
		Rate gyro	2	2 each at 1 truss station
		P/E accelerometer	30	2 each at 9 truss stations 3 each at 4 truss stations
3	Z-axis acceleration	P/E accelerometer	1	Tip of truss
4	Tip deflection	Laser & detector array	1	Tip & base of truss
5	Carriage position	Rotary encoder	2	1 each deploy carriage
6	Motor temperatures	Thermocouple	10	2 each carriage 1 each damper set
7	Truss member load	Strain gauge	48	2 each longitudinal & diagonal, truss bay 5 & 30
8	Roll support loads	Strain gauge	4	1 each deployment rail Roll support lug
9	Pitch support loads	Strain gauge	4	1 each pitch brace
10	Trunion pin loads	Strain gauge	10	2 each pin
11	Trunion pin motions	Potentiometer	5	1 each pin
12	Structure temperature	Thermocouple	84	TBD

SECTION 5

PRELIMINARY SYSTEM TEST PLAN

5.1 INTRODUCTION

The MAST or Space Construction Experiment (SCE) is proposed as a basic early shuttle flight experiment that will be integrated with the NASA, LaRC developed, Structures Technology Experimental Pallet (STEP) and flown in the Space Shuttle as a secondary payload of opportunity. Flight testing is to be performed on a non-interference basis with primary payloads. The basic experiment will consist of a large deployable truss structure equipped with controls and instrumentation to allow testing of predicted dynamic and structural behavior and deployment/retraction capabilities.

5.1.1 <u>PURPOSE</u>. The System Test Plan (STP) provides the policies, plans, and overall requirements for the testing to be accomplished for the SCE program. The plan only address the testing and flight of MAST configuration 1, see sections 2 and 3, which is the proposed initial experiment configuration. The STP encompasses all levels of testing to be performed in the SCE program. This includes development testing, qualification testing, acceptance testing, ground operation testing, STEP/MAST compatability testing and flight test operations.

5.1.2 <u>GROUND RULES AND ASSUMPTIONS</u>. The SCE test program shall be conducted in accordance with the following ground rules and assumptions:

a. Only one SCE test article will be produced for ground and flight testing.

b. Major ground simulation tests are planned using LaRC facilities.

c. Flight certification testing will be primarily performed at the system level to minimize the cost of verifying overall flight worthiness of the experiment.

d. Integration of the test article with STEP and STEP/MAST compatability testing will be conducted by LaRC.

e. The flight test operations will be conducted aboard the STS Space Shuttle Orbiter.

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5.1.3 TEST PROGRAM SUMMARY. The test program flow diagram (Figure 5-1) describes an orderly progression to meet the SCE program objectives and requirements. This test program is required to assure the performance of the flight experiment hardware and to verify the technologies required to accurately predict flight test performance of the structure and the structural damping subsystem.

The material and subcomponent testing will allow system manufacturing and design problems, and math modeling uncertainties, to be evaluated and resolved during the design phase. The flight acceptance tests will verify the flight worthiness, and functional capability of the SCE.

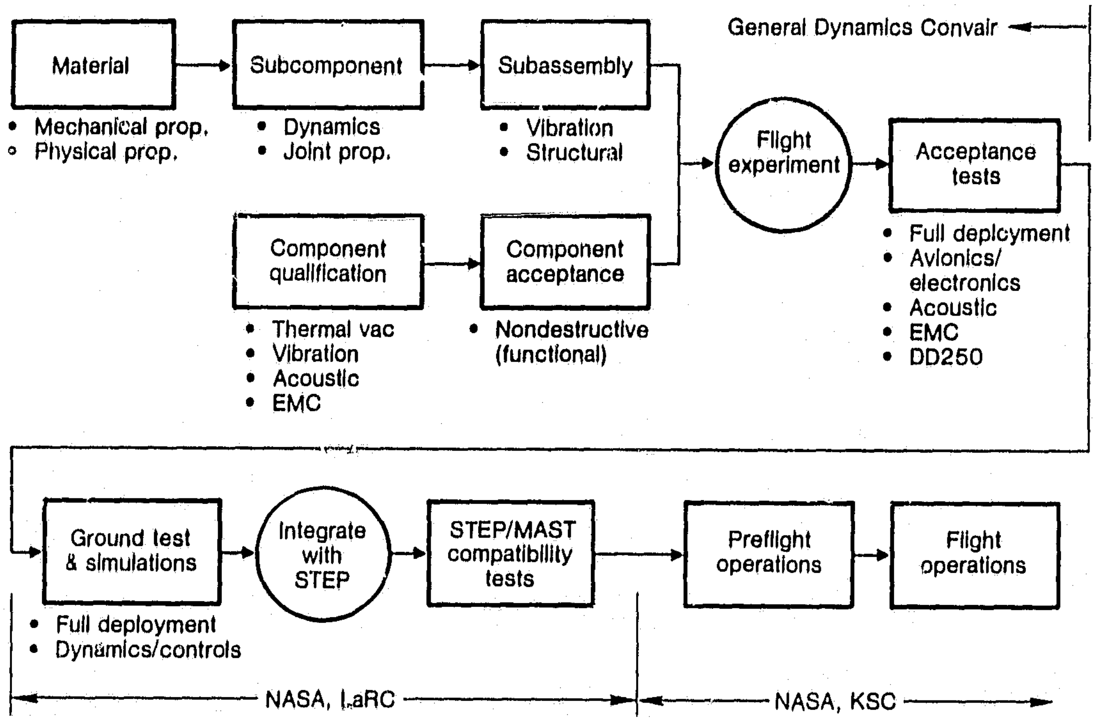


Figure 5-1. SCE Test Program Flow Diagram

5.2 DEVELOPMENT TESTS

Development testing for SCE is planned to provide early solution to manufacturing and design problems, and to identify key characteristics of hardware. Materials, subcomponents, and subassemblies will be tested in progressive stages to ensure earliest recognition of possible problem areas.

Adapting existing flight-qualified torque wheels and rate gyros to this application will be a long-lead-time consideration. Manufacturing of the deployable truss will be a major cost driver and will require some development to achieve a cost-effective precision design.

Structural tests utilizing a 5-bay truss segment will ensure compatibility of the final truss design with the operational environment. It will also allow structural dynamics characteristics to be measured for verification and refinement of the math model for full-scale assembly performance predictions.

5.2.1 MATERIALS TESTS. Truss tube and fitting composite material specimens will be tested to measure mechanical properties and outgassing characteristics. Preproduction tube specimen and node fitting material test coupons will be tested to establish longitudinal and transverse strength, compression strength and modulus; shear strength and shear modulus; and coefficient of thermal expansion (CTE) characteristics over the full range of operating temperatures. Truss composite materials, adhesives, bonding agents and other non-metallic materials will be tested or otherwise verified to be in accordance with Space Shuttle payload requirements for toxicity, outgassing, and vacuum stability.

5.2.2 SUBCOMPONENT TESTS. The following subcomponent tests will be performed:

a. Subcomponent Tests to Support Structural Dynamic Modeling. Structural subcomponents to be tested are shown in Table 5-1. The basic information which is required to simulate each component consists of the axial spring rates of the struts and braces, the cross-sectional moments of inertia of the deployment rails, a stiffness or flexibility matrix for the joint fittings, and the weight of each of the components. With the exception of the moment-of-inertia, each of these characteristics can be measured statically. Measurements of the concentrated masses will include the mass moments-of-inertia about the three basic axes. Sufficient quantities of each strut and node fitting configuration will be tested to establish a statistical population of values.

Table 5-1. Structural Components to be Characterized

Item	Measurements
Struts Node Fittings Pitch Brace Roll Braces Tip Package	Spring rates and mass properties

Cross-sectional moments of inertia are not directly measurable quantities and, thus, they must be obtained indirectly. A comparatively easy method of obtaining these parameters is to support the beam on wires located at or near the nodal points of the first free-free mode and then shake the beam to excite this first mode. Using the first frequency thus obtained, the cross-sectional moment-of-inertia may then be calculated.

b. Truss Strut and Node Fitting Assemblies Tests. Preproduction samples of each truss strut configuration and node fitting configuration will be subjected to a series of tests as follows:

1) Joint coupling effects of each pin joint configuration will be performed to measure joint behavior under static and dynamic loading conditions in the expected environment of temperature cycling and vacuum. Zero free play, thermal conductivity and electrical conductivity across each joint and hinge will be evaluated. Node-to-node thermal stability will be measured for conformance to near-zero CTE requirements. Joint swiveling torques will be measured. Bonded joint integrity will be verified.

2) Buckling stability and post buckling strength of each strut configuration will be measured. Strut specimens will be tested to failure in tension and compression.

3) Node joint ultimate strength tests under representative loading conditions will be performed on samples of each node fitting configuration.

c. Damper Set Tests. An engineering test article of a torque wheel actuator assembly will be assembled using a space qualifiable torque motor and rate gyro and connected to a simple control system. Damping performance of low modal frequencies will be evaluated using a simple cantilevered beam.

5.2.3 SUBASSEMBLY TESTS. The prediction of the dynamic reponse of the SCE requires the development of a finite element simulation of the system. This digital model may then be used to predict the dynamic response of the system due to excitations such as the forces and moments generated by the vernier reaction control system. MSC/NASTRAN is the basic finite element system which will be used and is basically a structural simulation made up of elements such as bar, tubes, rods and concentrated and distributed masses. In order that confidence may be gained in the adequacy of this digital model to simulate the "real world," it is necessary that ground tests be accomplished which verify this simulation.

Upon completion of the component tests, the next step is a vibration test of a separately manufactured segment of the SCE truss. The test truss will be mounted vertically as a cantilever and excited with electrodynamic shakers over a frequency range of essentially zero to 50 Hz as shown in Figure 5-2. Natural frequencies and mode shapes will be obtained and compared with the eigenvalues and eigenvectors which will be obtained from a finite element analysis of the truss segment. Use will be made of the component tests in assembling this finite analysis simulation and the total procedure will be a step in gaining confidence in the ability to predict modal frequencies and mode shapes of the full flight article.

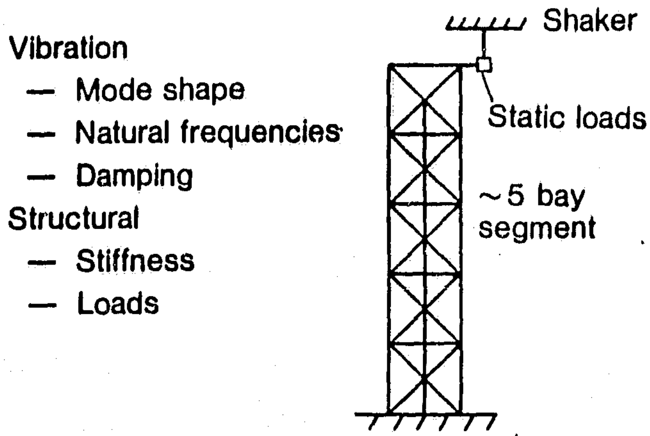


Figure 5-2. Fivebay Truss Segment Test

At the conclusion of the dynamic testing a load fixture will be installed on the upper end of the truss segment. Static proof loads will be applied axially in each direction then torsionally in each direction. Static loads and truss tip deflections will be measured. Strut loads will be measured by attached strain gauges. This test will demonstrate the ability of the truss to withstand predicted flight structural loads, correlate axial and torsional stiffness results with that predicted by the structural model and evaluate strain gauge measurement techniques for strut loads.

5.3 COMPONENT QUALIFICATION TESTS

Component qualification testing is intended to assure the success of subsequent subsystem, system, and flight testing. All test specimens will have successfully completed a functional checkout and acceptance testing including burn-in (if required) before qualification testing.

Environmental qualification test requirements will comply with JSC-07700, Volume XIV (Revision G, September 26, 1980), "Space Shuttle System Payload Accommodations." All newly designed components will be qualified and existing qualified components will be reviewed and retested as required to ensure full compliance with Shuttle requirements. Components environmental testing will be minimized by performing major tests at the integrated system level during Flight Certification Testing to preclude numerous individual component and subassembly tests.

Component qualification tests are sumarized in Table 5-2.

Table 5-2. Component Qualification Test Program Summary

	Ambient Oper-ating	Vacuum or Thermal Vacuum	Vibration	Acoustic	EMC	Shock
Damper Package	X	X	X		X	
Deployment Carriage	X	X			X	
Bus Interface Unit	X	X	X	X	X	X
Tip Mass Ejector	X	X	X		X	X

5.3.1 DAMPER PACKAGE. The damper package, consisting of six torque wheel/rate gyro actuators will be functionally tested in ambient conditions to set up the phasing. The package will be tested for EMC and subjected to a functional thermal vacuum test and vibration test.

5.3.2 DEPLOYMENT CARRIAGE. The deployment carriage will be run through a series of operating cycles in thermal vacuum to confirm its durability and reliability. It will also be tested for EMC.

5.3.3 BUS INTERFACE UNIT. The bus interface unit will be functionally tested by supporting the damper tests. It will also be vibration tested, acoustic tested, EMC tested and shock tested.

5.3.4 TIP MASS EJECTOR. The tip mass ejector will be functionally tested in both ambient and thermal vacuum environments. The unit will be demonstrated in the vacuum environment after being subjected to vibration and shock testing. EMC testing will also be performed.

5.4 COMPONENT ACCEPTANCE TESTS

Component acceptance tests are formal tests required to demonstrate that the hardware and associated data is in compliance with specifications and ready for delivery to NASA or for qualification test. These tests are designed to detect deficiencies in workmanship, material or quality. They are normally non-destructive in nature and performed on all deliverable units. They include functional testing and may include environmental testing if necessary to verify performance.

5.5 SPACE CONSTRUCTION EXPERIMENT ACCEPTANCE TEST

Prior to acceptance and delivery of the Space Construction Experiment and associated end items, a series of formal acceptance tests will be conducted. These tests will be witnessed by the NASA and will culminate upon delivery of test data demonstrating performance of equipment to prescribed test specifications.

The acceptance test will include, but not be limited to:

5.5.1 FULL DEPLOYMENT/RETRACTION TEST. Tests of the deployable truss and deployment/retraction mechanism will be conducted in the horizontal position. Deployment and retraction will be with the aid of support dollies on low friction rollers. The truss will be fully deployed and fully retracted three times.

Electrical interface compatibility tests will be performed on the power, control and data services, and displays and operator controls interfaces. The commands to the MAST avionics elements will be by the STEP simulator (a GFE stripped-down functional version of STEP) throughout the test. Monitoring of all applicable parameters will be provided by the contractor.

5.5.2 EMC TEST. The assembled SCE (MAST) with avionics will first be tested in the un-deployed mode in a shielded screen room to MIL-STD-461 procedures (modified as necessary for grounding, etc) for both radiated and conducted interference. The obtained data will provide important information on critical frequencies for the deployed MAST EMC tests.

The deployed MAST EMC tests will be done in a RF quiet area (possibly at night) since screen rooms are not that large. Radiated tests will be performed in the deployed state with the measurement antenna being moved along the truss due to short range. Both the ambient and MAST energized measurements will be made. Also EMC measurements will be made as the carriage drive is in operation during deployment.

5.6 GROUND TESTS AND SIMULATIONS PLAN

These tests are proposed to be conducted at NASA, LARC. The initial structural dynamics model will derive data on struts, joints, fittings, mass properties, etc., from the component tests. The model will be tested by performing subassembly tests of the modeled 5-bay structural segment. Structural interface tests of the flight experiment support structure will allow interface deflections at the base of the truss to be computed from measured flight loads. Deployment tests and dynamics and controls tests will allow the structural dynamic and control models for the flight test article to be evaluated and provide a data base for evaluating the effectiveness of ground test of partially deployed configurations in ensuring accurate flight test performance predictions.

5.6.1 DEPLOYMENT TEST. The deployment test will evaluate the effects of deployment rates and acceleration on the behavior of the structure and will finalize the functional operating parameters for the deployment/retraction mechanisms and controls in a simulated zero-g condition. The test will consist of varying drive rates and rate profiles and of measuring the loads and disturbances in the truss structure. The test fixture as shown in Figure 5-3 will consist of a synchronized deployable suspension system. The suspension cables will be translated in unison with the truss structure by using a truss deployment carriage digitally controlled by the STEP simulator.

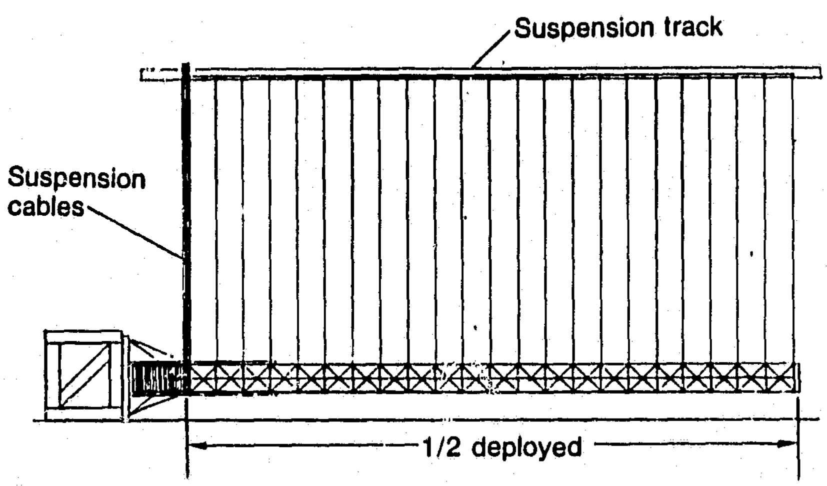


Figure 5-3. Ground Deployment Test Concept

5.6.2 STRUCTURAL DYNAMICS AND CONTROL TEST. The partially deployed structure (Figure 5-3) will be used to conduct a series of dynamic and controls tests. For a horizontal excitation it is necessary to ensure that the pendulum frequency of the zero-g suspension cables is well below the lowest modal frequency of the structure. This limits the length of structure that can be tested, unless very long suspension cables can be accommodated at the test facility.

The approach used for the structural dynamics ground test will recognize that the suspension will be part of the ground test dynamic system. Adjusting the model of the entire system to match test results should give the proper mass and stiffness matrices for the flight structure. The deployed structure will also provide an opportunity to check out active damper performance and component installation.

The test will be performed on a 50 percent deployed truss, which is the initial deployed length that will be tested during flight test operations. A modal survey in the horizontal plane will be performed using the damper set torque wheels for excitation. Following excitation tests the damper sets will be activated and damping performance evaluated. The dynamics and controls tests will be performed in each of two planes by rotating the truss 90° about the longitudinal axis after the first test.

The dynamic model will include the suspension and gravity effects on the structure. Test results will be used to adjust the strutural dynamic model as required to predict on-orbit dynamics.

5.6.3 STRUCTURAL INTERFACE TEST. The SCE support structure will be installed in a rigid test fixture with simulated STEP retention fittings to retain the structure at its six trunnion pins. A rigid load fixture will attach to the SCE support structure at all of the deployable truss attach points.

Force input and deflection will be measured at each of the truss attach points in real time along with the trunnion pin loads and motions while moments are applied to the load fixture about the pitch, yaw, and roll axis. The loads and deflections data will be used to generate a stiffness and/or flexibility matrix for the finite element simulation of the SCE.

5.7 SCE/STEP COMPATABILITY TESTS

Following completion of the Ground Tests and Simulations the SCE will be integrated with the STEP. This will be performed at NASA, LaRC. Following physical integration power will be

provided and functional testing will be conducted to verify the operating interfaces between STEP and SCE and to verify performance of the software.

5.8 GROUND OPERATIONS PLAN

The general plan for SCE/STEP ground operations to be conducted at KSC during both preflight preparations for launch and subsequent postflight activities after landing is described in the following subsections.

5.8.1 PREFLIGHT GROUND OPERATIONS AT KSC. Initial preflight operations will be performed in a Payload Processing Facility (PPF) to be designated for SCE use. PPF tasks include receiving and inspection, refurbishment, preparation, and checkout operations as necessary to establish SCE/STEP system flight readiness.

The SCE/STEP will then be transferred to either a Vertical or Horizontal Processing Facility where it will be integrated with other assigned coflight manifested payloads (into a complete cargo assembly) and processed for launch using conventional Shuttle Orbiter preflight procedures. Either the vertical or the horizontal processing mode may be used for the SCE/STEP, permitting flexibility in its selection for compatibility with other payloads. Although basically the same operations are performed in either mode, each is discussed separately because different facilities/procedures are used in each.

5.8.1.1 Payload Processing Facility (PPF) Operations. The activities to be performed in the PPF, encompassing approximately six weeks of SCE preparation and checkout tasks, are described below.

a. Upon arrival at the designated KSC PPF, the SCE/STEP equipment will be unpackaged. An initial inspection will then be performed.

b. Other items to be received and inspected in the PPF will include the flight instrumentation components (strain gages, thermocouples and accelerometers) and associated cabling, and a simple ground test switch panel.

c. The truss assembly will be deployed horizontally while installed in its handling and transportation dolly. A preliminary electrical check will be performed. In preparation for truss extension, the truss sidemembers will be manually unlatched and positioned.

d. The truss will then be fully extended (in increments of several bay groups at a time). As the truss is extended, GSE support dollies will be manually positioned under the structure to provide physical support in the extended configuration and to allow the necessary movement of the truss across the floor.

e. In the fully extended position, a complete inspection of the mast structure will be accomplished and any discrepant areas refurbished.

f. Flight instrumentation, electrical equipment, and harnessing will then be installed on the SCE and applicable functional checks and calibrations performed. Other checks will include an end-to-end test of the tip mass jettisoning system.

g. The mast will then be retracted, and an inspection performed in the retracted configuration. This will be followed by a final extend/retract cycle to verify that the added instrumentation components and harnessing do not adversely affect the deployment and retraction processes. During this final cycle, prior to retract, a complete cleaning of the mast structure will be performed.

h. The truss will be fully retracted and folded to its stowed configuration. The truss and STEP will be lifted by handling sling from its dolly. The SCE/STEP will be installed vertically on the FSE support structure which will be mounted on its handling and transportation trailer.

i. The SCE/STEP will then be prepared for transportation to either the Vertical Processing Facility (VPF) or the Operations and Checkout Facility (O&C) which would be the Horizontal Processing Facility (HPF). The subsequent preflight operations are summarized in Figure 5-4 and described in the following subsections.

5.8.1.2 Vertical Processing Operations. In the vertical processing mode, preflight operations will be performed at three separate facilities: the PPF (previously discussed above), the VPF, and the launch pad. The general flow sequence of operations to be performed in each of these facilities for vertical processing of the SCE/STEP is depicted in Figure 5-5. Timespan requirements for the major activities involved are shown in Figure 5-6. Further description of the VPF and launch pad operations is provided below.

Upon arrival at the VPF, the SCE/STEP will be removed from its handling fixture and placed in the Vertical Payload Handling Device (VPHD) where it will be physically integrated with its

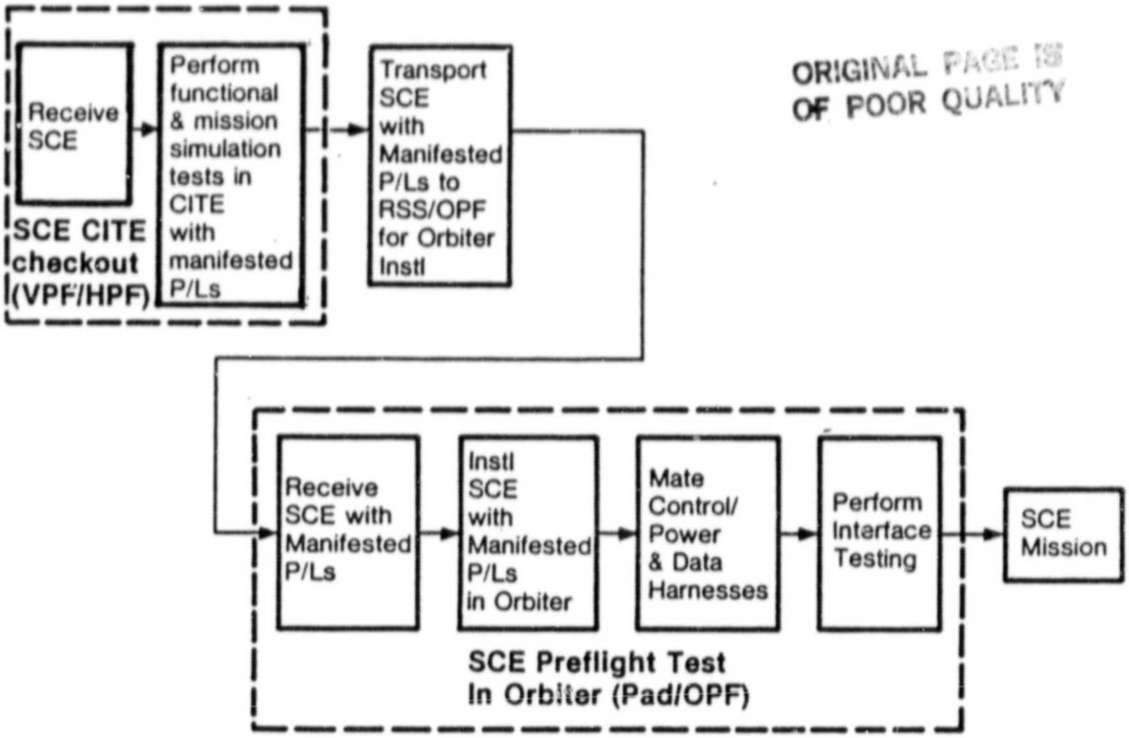


Figure 5-4. SCE Preflight Ground Operations Sequence Summary

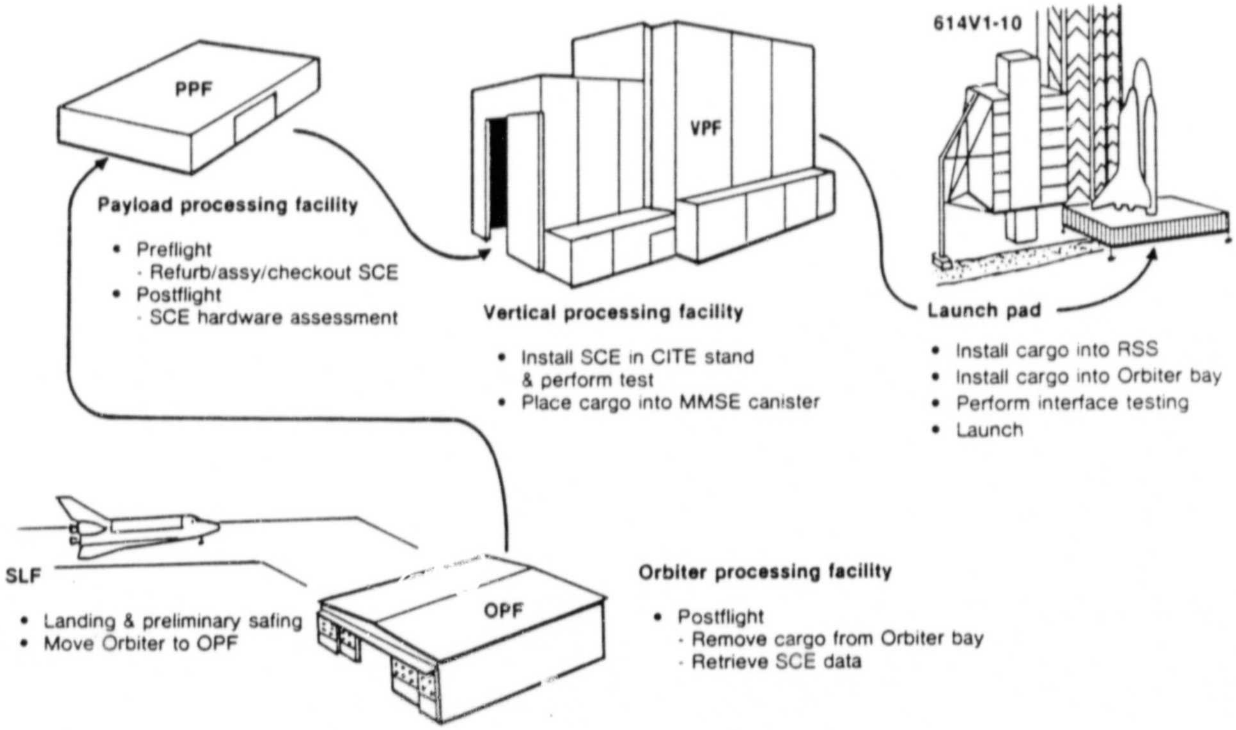


Figure 5-5. SCE Vertical Processing Operations

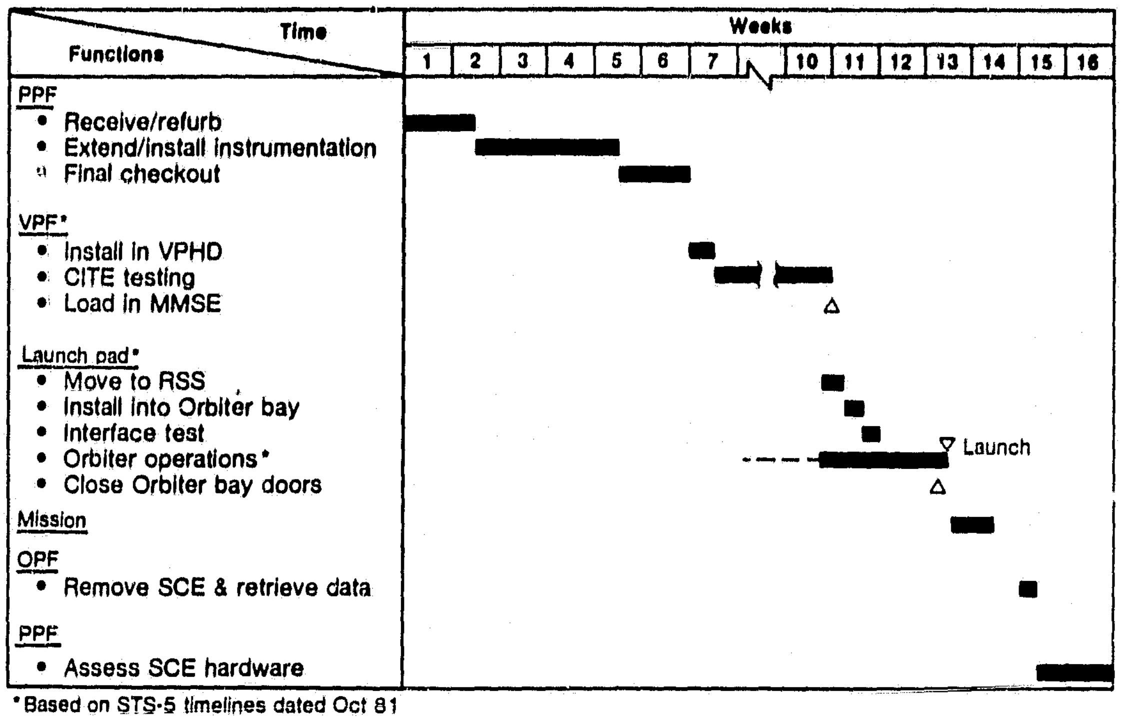


Figure 5-6. SCE Vertical Processing Timeline

other coflight manifested payloads. The SCE/STEP (and the coflight payloads) will then be connected to the Cargo Integration Test Equipment (CITE) which electrically simulates the flight Orbiter. The orbiter standard switch panel and the experiment control panel to be used for SCE control is provided in the simulated Aft Flight Deck, and all interface cabling will be installed within the test stand as appropriate.

Following preliminary interface tests, approximately three and one-half weeks of integrated CITE testing with the manifested payloads will be performed. The SCE/STEP portion of these CITE tests will consist primarily of functional and mission simulation tests.

After completion of CITE testing, the SCE/STEP and manifested payloads will be placed into the Multiuse Mission Support Equipment (MMSE) canister and transferred to the launch pad aboard the MMSE transporter.

At the launch pad, the payloads will first be placed in the Rotating Service Structure (RSS) which in turn will be used to install the payload into the Orbiter bay. After physical installation is complete, interface harnesses will be connected.

A series of brief interface checks will then be performed to verify all SCE/STEP power, control, and data circuits. From this point on through launch and up until SCE/STEP mission deployment, the SCE/STEP is essentially dormant except for final pyrotechnic bolt installation and connections.

After completion of approximately one additional week of Orbiter checkout operations, the Orbiter and its payload are ready for launch.

5.8.1.3 Horizontal Processing Operations. In the horizontal processing mode, the SCE/STEP will be cycled through five separate facilities during preflight operations: the PPF (discussed previously), the O&C (which acts as the horizontal processing facility), the OPF, the VAB, and the launch pad. The general flow sequence of operations through these five facilities is illustrated in Figure 5-7. Timespan requirements for the major activities involved are shown in Figure 5-8. Description of the O&C, OPF, VAB and launch pad operations are provided below.

Following checkout in the PPF, the SCE/STEP will be transferred to the O&C facility for horizontal processing. The operations to be performed in the O&C are virtually the same as those performed in the VPF except they are conducted with the SCE/STEP (and other coflight payloads) oriented in a horizontal rather than vertical attitude.

Upon arrival in the O&C, the SCE/STEP will be placed in a horizontal test stand and integrated with its other coflight payloads. The Cargo Integration Test Equipment (CITE) will then be connected to the SCE/STEP, followed by integrated CITE testing with the other manifested payloads. The SCE portion of these CITE tests will consist of functional and mission simulation tests.

After completion of CITE testing, the SCE/STEP and manifested payloads will be placed into the MMSE canister and transferred to the OPF.

At the OPF, the SCE/STEP and coflight payloads will be installed in the Orbiter cargo bay. After physical installation is complete, all SCE/STEP to Orbiter interface harnesses will be connected.

A series of brief interface checks will then performed to verify all SCE/STEP power, control, and data circuits. From this point on through launch and up until SCE/STEP mission deployment, the SCE/STEP is essentially dormant. No further access is required.

Following these interface checks, the Orbiter cargo bay doors are closed and the Orbiter will be towed to the VAB.

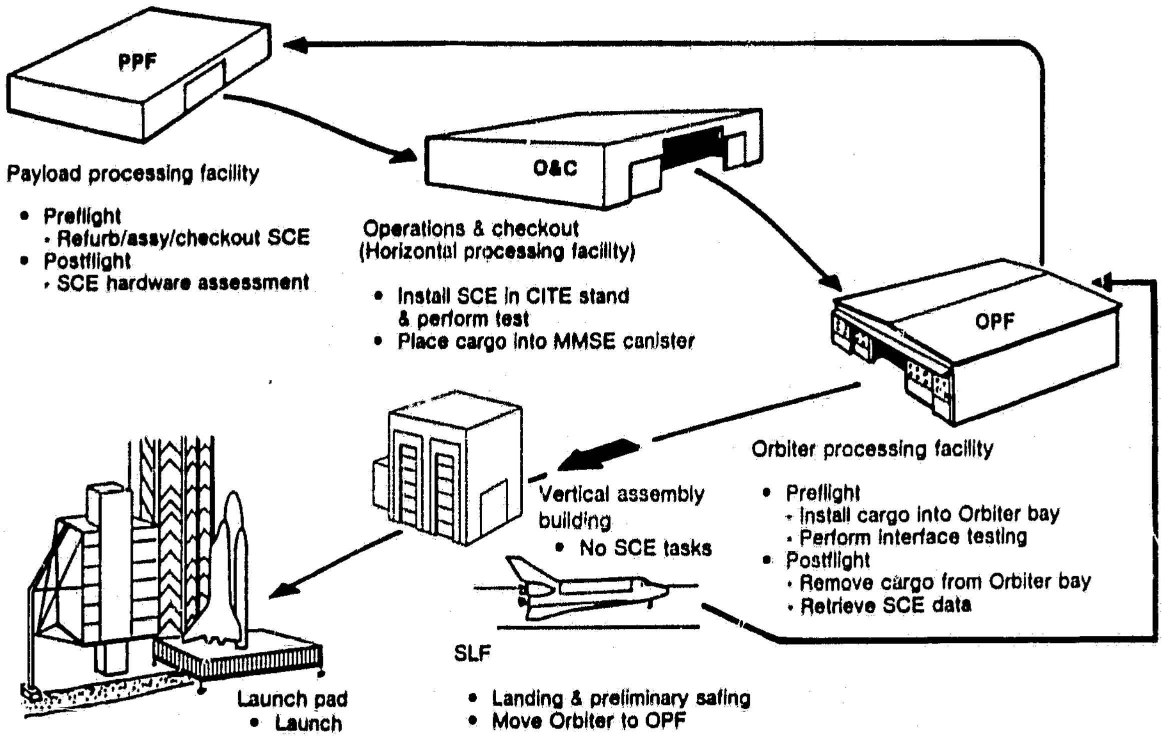
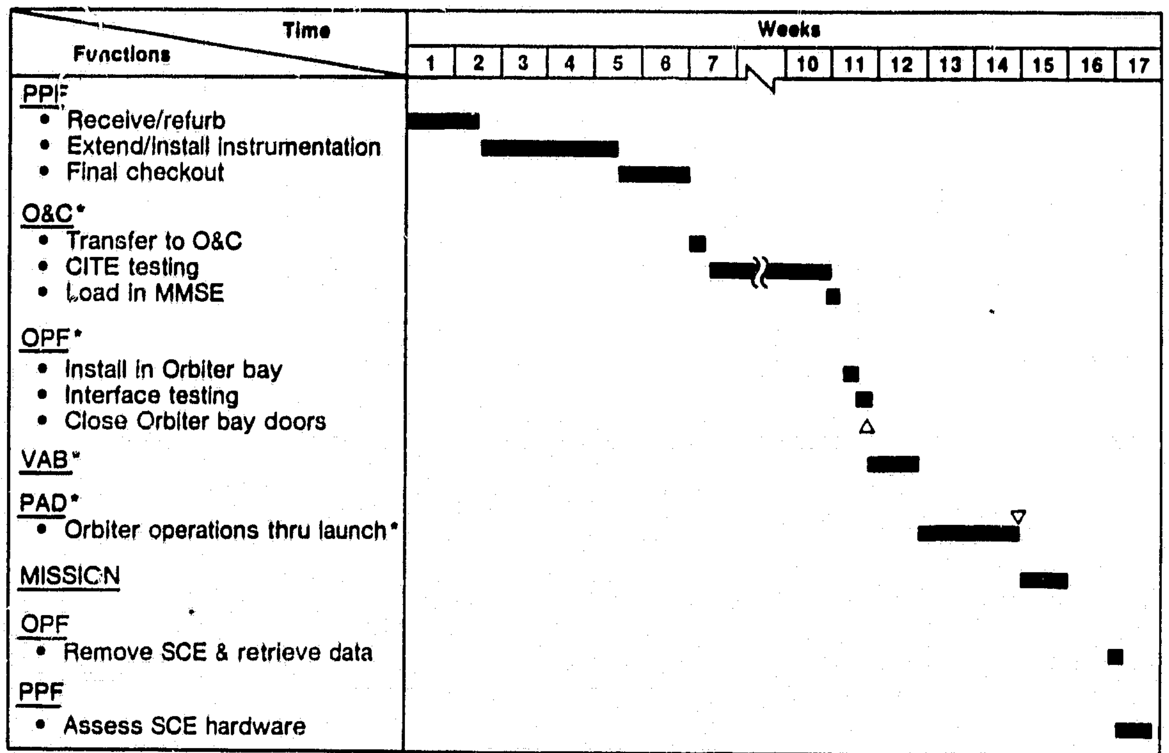


Figure 5-7. SCE Horizontal Processing Operations



*Based on STS-5 timelines dated Oct 81

Figure 5-8. SCE Horizontal Processing Timeline

In the VAB, the Orbiter will be erected to a vertical attitude and mated to the external tank and solid rocket boosters (SRB's) on the Mobile Launch Platform (MLP). These operations involved approximately one week of space shuttle activities only; no SCE operations are required.

After completion of the VAB operations, the entire vehicle assembly (with the SCE/STEP installed in the Orbiter cargo bay) will be transported to the launch pad and prepared for launch. These operations require approximately three weeks of space shuttle activities. Final SCE/STEP operations require installation of pyrotechnic bolts in the tip mass ejection mechanism.

5.8.2 POSTFLIGHT GROUND OPERATIONS AT KSC. Following completion of the flight mission, the SCE/STEP will be returned to KSC by the Orbiter. The postflight operations required at KSC are described below. A block diagram of these operations is shown in Figure 5-9.

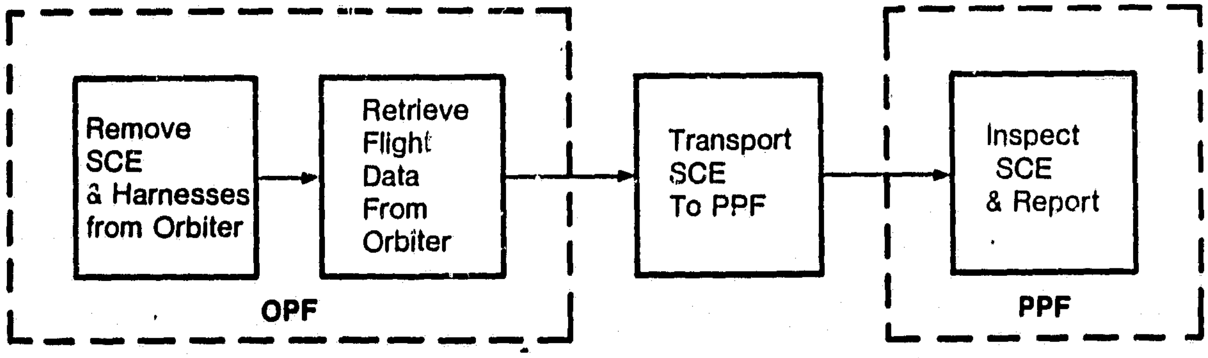


Figure 5-9. SCE/STEP Postflight Ground Operations Sequence

After the mission is completed and the Orbiter has landed, it will enter the OPF. The flight data recorder tapes will be removed from the Orbiter. The SCE/STEP will be lifted out of the Orbiter bay using the MMSE strongback and place on the shipping/handling trailer. The SCE/STEP will be transported to the PPF.

The assembly will be removed from the ASE support structure and installed on its handling and transportation dolly. The truss will be electrically connected to the support structure subsystems. The power supply will be connected to the SCE/STEP and the truss will be fully deployed on its support dollies.

The structures and components will be inspected for evidence of damage and degradation. All discrepancies will be documented.

Following the inspections the truss will be repackaged and prepared for final disposition.

5.8.3 GROUND SUPPORT EQUIPMENT (GSE) REQUIREMENTS. GSE items required to support SCE/STEP preflight and postflight ground operations are listed in Table 5-3.

Table 5-3. GSE Items for the SCE

Item	Quantity	Purpose
Step Simulator (GFE)	1	Checkout, deployment & retraction control
Truss Handling & Transportation Dolly	1	Ground handling and transport of truss assembly
Payload Handling & Transportation Trailer	1	Ground handling & transport of ASE
Truss Support Dollies	20	Support truss during ground deployment
Payload Handling Sling	1	Pick-up ASE support structure or fully assembled payload
Truss Handling Sling	1	Pick-up truss assembly
Cable Kit	1	Interconnect power, data and control functions for ground test and checkout.

5.9 FLIGHT OPERATIONS PLAN

The flight test sequence will require one day of the total mission. The first few days in orbit will be used to deploy the satellite payloads. Following these operations the SCE activities will be initiated.

5.9.1 EXPERIMENT SEQUENCE

The test sequence is shown in Table 5-4. Initial deployment is to half length. This is for two reasons: first is to provide an opportunity for evaluation in a conservative condition and

Table 5-4. Test Sequence

1. Deploy structure to half length (A6)
2. Random shake, three axes one at a time (A5, B3)
3. Damp structure with Local Velocity Feedback (LVFB) (A1, A2)
4. Random shake, three axes at same time (A5, B3)
5. Damp structure with LVFB (A1, A2)
6. Sine excitation & free decay of first bending mode (A5, B3, B4)
7. Deploy structure to full length (A1, A2, A6, B2, B5)
8. Random shake, three axes one at a time (A5, B3)
9. Damp structure with LVFB (A1, A2)
10. Random shake, three axes at same time (A5, B3)
11. Damp structure with LVFB (A1, A2)
12. Sine excitation & free decay of first bending mode (A5, B3, B4)
13. Release joint loads & repeat 12 (A5, B3, B4)

second is to obtain data for comparison with the half-deployed ground test. Since the half-deployed ground configuration will have higher frequencies than the fully deployed case, suspension modes should be easier to separate from the structural modes and the correspondence with flight data may be better.

Initially, the three axes are evaluated one at a time using a random shake or excitation technique. Generating modal data with random excitation and post-flight computer reduction has been selected since it is considerably more efficient timewise than seeking out specific modes. After data is taken for an axis, the Local Velocity Feedback (LVFB) dampers are engaged to speed up settling and provide a quiet structure for the run. Following the evaluation of three axes one at a time, data is taken for all three axes excited simultaneously. Since the random excitation technique linearizes the results, the last test at half length uses the dwell technique to identify non-linear structural behavior. The first bending mode is excited by sinusoidal excitation, the excitation is removed, and data is taken while the mode decays in amplitude.

Next, the experimental structure is deployed to full length and the half-length sequence repeated. One additional evaluation is added to provide data on the damping influence of joint free play. Selected joints are unloaded and the sinusoidal excitation followed by free decay is repeated. Table 5-4 also lists the technical needs that are addressed by each sequence.

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The flight test sequence is shown in Figure 5-10. In addition to the actual test time, significant time is required for preparation, RMS operations, and securing. The timed sequence of the actual testing is presented in Figure 5-11. Since the time required to take data is set by oscillations of the first mode of interest, the fully deployed structure with its lower frequencies takes considerably longer to test than does the half-deployed structure.

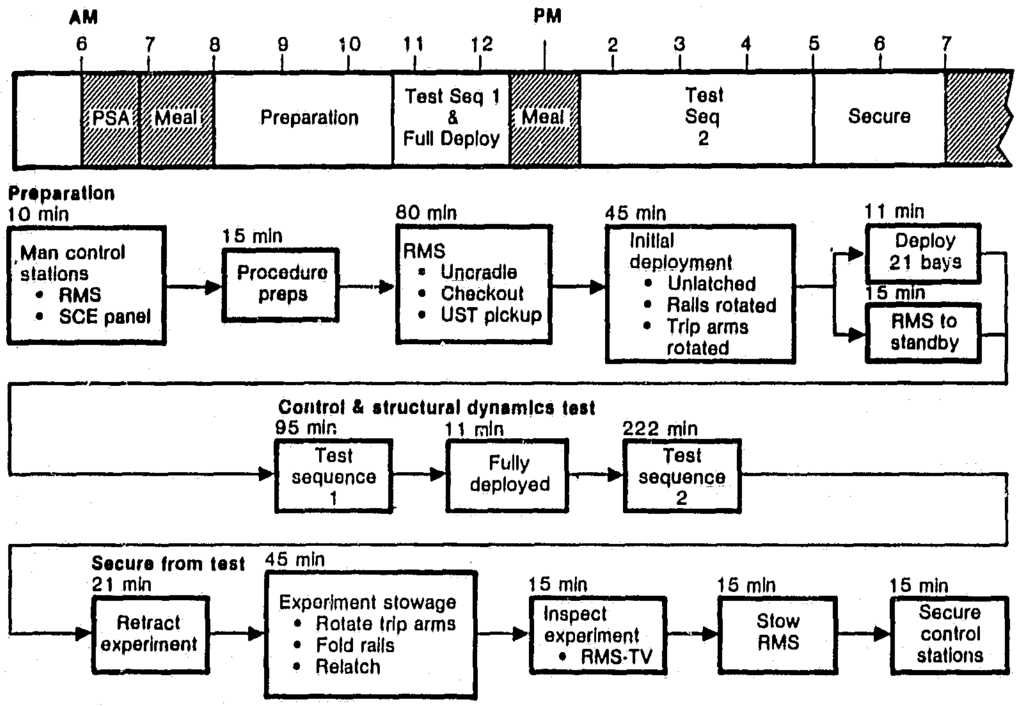

Figure 5-10. Flight Test Operations Sequence & Timelines

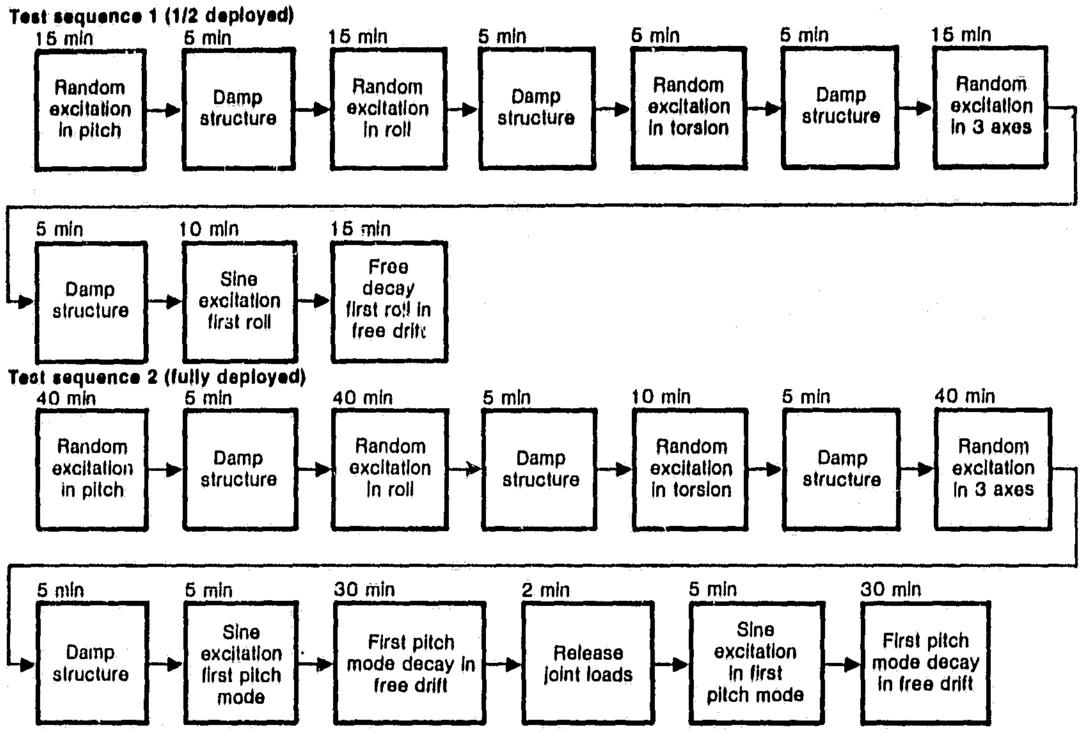

Figure 5-11. Dynamics & Controls Flight Test Sequences

SECTION 6

PROGRAM PLAN

6.1 COST ANALYSIS

A preliminary ROM cost estimate has been prepared for the candidate Space Construction Experiment (SCE/MAST) concept described in this report. Annual funding requirements have also been developed in accordance with the program schedule discussed in Section 6.2.

6.1.1 METHODOLOGY. The parametric cost model used for this analysis is an adaptation of our Space System Life Cycle Cost (SSLCC) model tailored specifically for the SCE. The SSLCC model was developed in-house over the last several years and used extensively for the SCAFEDS, Geostationary Platform Study, OTV study, and other studies of similar flight vehicles.

Initially a cost-related work breakdown structure (WBS) was developed that included all elements incurred by the SCE project for each program phase: development, production, and operations. Operations costs are not addressed in this study. This cost WBS then sets the format for the estimating model, the individual cost estimating relationships (CERs), cost factors, or specific point estimate requirements, and the cost estimate output. Estimates are then made for each cost element either at the breakdown level shown or, in certain cases, one level lower. These estimates are then accumulated to provide the cost for each program phase.

The estimating methodology varies with the cost element and with the availability of historical data or supplier estimates. Where sufficient detailed definition of the hardware and tasks are available, detailed estimates of labor and material may be developed. This procedure was used to develop the cost of the deployable truss beam. Drawings, parts lists, and fabrication description were used to generate material procurement requirements and labor hours for design and analysis, tooling design and fabrication, test article manufacturing, development test, GSE design and fabrication, sustaining engineering and tooling, acceptance test, and quality assurance. These labor and material requirements are then translated into dollar projections using appropriate labor rates.

For other new hardware, parametric CERs are used. These CERs have been derived for various families of hardware and many subcategories, representing differing levels of complexity.

They are derived from available historical cost data or detailed estimating information and relate cost to a specific driving parameter such as weight, area, power output, etc. For example, the various experiment structural items (other than the truss beam) were estimated using CERs. Engineering point estimates were used for specific pieces of known equipment where the definition data were sufficiently detailed or the hardware item was existing equipment and cost data were available; for example, ROM estimates for some of the dynamic test equipment items (gyros, etc.)

The remaining wraparound cost elements, such as system engineering and integration, program management, etc., are estimated using cost factors consisting of appropriate percentages of the applicable related program effort.

The nonrecurring or development phase includes all one-time tasks and hardware required to design and test the equipment. It includes the design and analysis of all ground and flight hardware including structural analysis, stress, dynamics, thermal, mass properties, etc. The nonrecurring category also includes all component development and test through component qualification as well as all component development test hardware. In addition, this phase includes: software development; system engineering and integration; system level test hardware and the engineering test prototype and qualification article; and system test. Since the prototype approach will be used for this experiment, a single flight article will be manufactured and all system level testing will be accomplished using the flight vehicle, which will then be refurbished and updated to flight configuration. Also included in this phase are GSE design, development, test, and manufacture; facilities; and overall program management and administration.

The production phase (unit cost estimate) includes all tasks and hardware necessary to fabricate one complete set of flight hardware equipment. It includes all material and component procurement, parts fabrication, subassembly, and final assembly. In addition, this category includes the required quality control/inspection task, an acceptance test procedure for sell-off to the customer, and program management and administration activities accomplished during the manufacturing phase.

Operating costs, NASA ground testing, shuttle integration and Shuttle-user charges were not included in the cost analysis at this time.

6.1.2 GROUND RULES AND ASSUMPTIONS. The general ground rules assumptions governing the subsequent cost estimates are:

a. Costs are estimated in constant 1983 dollars.

b. Prime contractor fee is not included.

c. Costs are for the design, development, and fabrication of a single, flyable experiment.

d. All system development (non-recurring) testing required is accomplished using the flight article hardware which is then refurbished for flight.

e. These costs exclude NASA center test programs after flight article delivery.

f. No shuttle integration, mission operations or Shuttle-user charges are included.

g. The cost estimates presented are rough-order-of-magnitude costs, for planning purposes only.

6.1.3 WORK BREAKDOWN STRUCTURE (WBS). The WBS is a breakdown of all program life cycle elements, categorized or sorted into several levels of hardware and task or function-oriented end items, and serves to identify the cost elements to be included in the cost analysis task. This WBS contains all hardware and tasks associated with Phase C/D development and test, fabrication of flight hardware, and the activities incurred during the test flight. It serves as the basic format for cost reporting and programmatic data, and to organize, plan, and manage the subsequent program. The WBS developed for the SCE is shown graphically in Figure 6-1, and each element is briefly defined below.

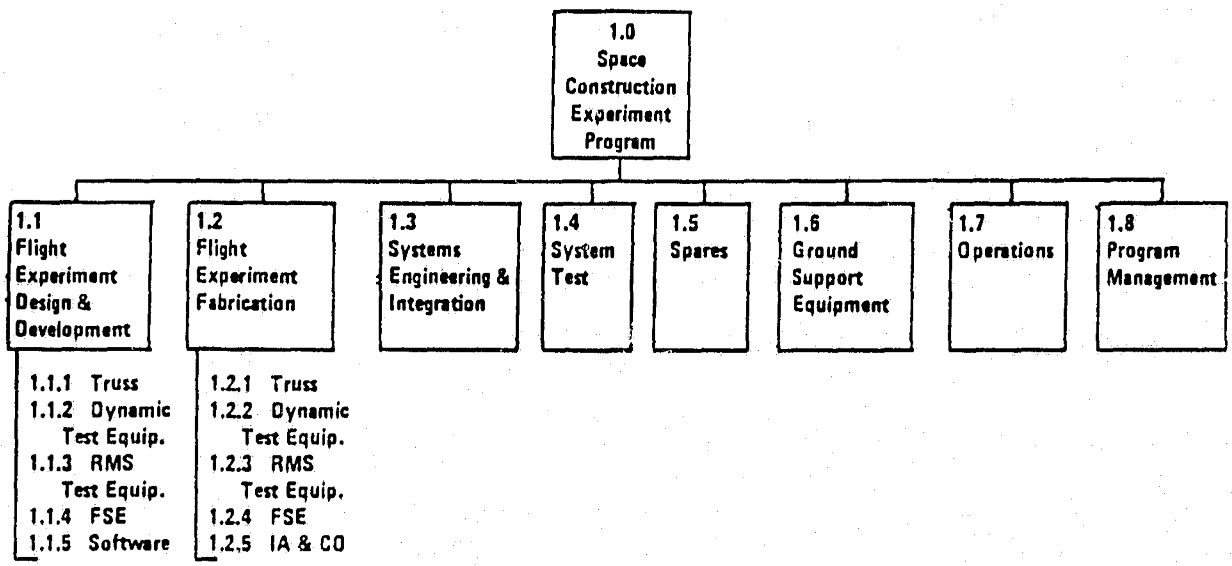

Figure 6-1. Space Construction Experiment WBS.

a. WBS 1.0 - Space Construction Experiment Program. This WBS element summarizes all effort and material required for the design, development, fabrication, assembly, test and checkout, and operation of the SCE.

b. WBS 1.1 - Flight Experiment Design and Development. The design and development activities include all tasks and hardware for design and development and testing of the SCE. It includes the required design and analysis for all ground and flight hardware, including structural analysis, stress dynamics, thermal, mass properties, etc. This nonrecurring category includes tooling, component development, and test through component qualification, as well as all component development test hardware. This element also includes software development.

c. WBS 1.1.1 - Truss. The deployable truss is the primary structural element being tested. It has a diamond cross section and 42 bays and is constructed of composite materials. Also included are the deployment mechanism, experiment support elements, and the tip mass.

d. WBS 1.1.2 - Dynamic Test Equipment. The equipment includes torque wheels and torque motor controllers, gyros, accelerometers, loads, displacement and temperature instrumentation, and their wiring harness. This equipment excites and measures vibrational modes and system parameters and provides active damping augmentation.

e. WBS 1.1.3 - RMS Equipment. The RMS test equipment includes special RMS end pieces, and special tools.

f. WBS 1.1.4 - Flight Support Equipment (FSE). The FSE consists of the truss support structure that provides the interface with STEP.

g. WBS 1.1.5 - Software. This WBS element consists of all labor, material, and computer resources necessary to verify the GFE software.

h. WBS 1.2 - Flight Experiment Fabrication. The flight experiment fabrication cost element includes all tasks and hardware necessary to provide one complete set of flight hardware equipment. It includes all material and component procurement, parts fabrication, subassembly, and final assembly. In addition, this category includes the required quality control/inspection task, an acceptance test procedure for sell-off to the customer, and program maangement and administration activities accomplished during the manufacturing phase.

i. WBS 1.2.1 thru WBS 1.2.4 - Subsystems. See above.

j. <u>WBS 1.2.5 - Integration Assembly and Checkout.</u> This WBS element consists of all effort and materials required to accomplish subsystem installation, final assembly, checkout, and recurring acceptance testing. These are all ground activities and culminate in sell-off to the NASA (DD Form 250).

k. <u>WBS 1.3 - Systems Engineering and Integration.</u> This WBS element summarizes all system level studies, analyses, and tradeoffs to support the development of requirements, specification, and interfaces necessary to direct and control the design of the overall system. It also includes all mission studies and analyses to establish requirements and planning for all phases of the mission and logistics activities. It also includes all product assurance activities consisting of safety, reliability, maintainability quality assurance, and parts, material, processes control.

l. <u>WBS 1.4 - System Test.</u> This WBS element summarizes all effort and hardware required to conduct and support all major system level non-recurring testing conducted by the contractor necessary to refine and validate the design and verify the accomplishment of the development requirements. They may include but not be limited to full-scale structural tests, integrated avionics tests, all-up functional tests, and payload functional and integration testing. This element includes test article refurbishment and reconfiguration; test planning, test analysis, preparation, and test operations; as well as test software and test support activities performed prior to delivery to NASA.

m. <u>WBS 1.5 - Spares.</u> The WBS element includes the procurement and/or fabrication of all spare and repair parts necessary for the development and operational period.

n. <u>WBS 1.6 - Ground Support Equipment (GSE).</u> This WBS element summarizes all effort and ma-erial required to define, design, develop, test and qualify, procure, fabricate, assemble, and checkout all GSE required to support the SCE during the development, manufacturing, and operations phase. It includes all necessary handling and transportation equipment, and functional checkout equipment.

o. <u>WBS 1.7 - Operations.</u> This WBS element summarizes all of the effort and materials required to support the experience during its operational phase. It includes all ground operation and STS integration activities, flight and mission operations, and operations support. Operations costs are not currently estimated.

p. WBS 1.8 - Program Management. This WBS element summarizes all of the effort required to manage, direct, and control the entire program. These functional tasks and activities include planning, organizing, budgeting, scheduling, directing, and controlling other administrative tasks to ensure the overall objectives of the program are accomplished.

6.1.4 <u>FLIGHT EXPERIMENT COST ESTIMATES</u>. Refinements made to the concept selected in the first two phases of the study (including integration with STEP and resizing of the truss) provided revised input that was used in the cost analysis. Using the updated information concerning the current configuration generated in this phase of study, new cost estimates were made. The results of this cost analysis are presented in Table 6-1. The total cost for the design, development, fabrication, and test of the SCE is approximately $11M exclusive of GFE items. The experiment flight hardware fabrication accounts for about $3.8M and the remaining $7.4M is required for design and analysis, component development and test, system engineering, the system level test, program, and program management. It should be noted that all system level testing and integration is conducted using the flight experiment equipment that is subsequently refurbished for flight configuration. Also included in this design and development cost is software at $0.1M, GSE at $0.2M, and spare and repair parts at $0.3M.

Table 6-1. Preliminary ROM Cost Estimates.

	Design & development	Flight article fabrication
Flight hardware		
• Structure	2.33	2.45
• Dynamic test equip/instrumentation	.97	.56
• RMS equipment	.01	.01
• Airborne support equipment	.66	.16
• Assembly & integration	—	.37
Software	.14	—
System eng & integration	.76	—
System test	1.61	.10
GSE	.21	—
Spares	.32	—
Facilities	—	—
Program management	.35	.18
Total	7.36	3.83
Grand total	11.19	

The majority of the hardware design and development cost is required for structure and mechanisms including the truss, its deployment mechanism, and the support structure for mounting the SCE in the STEP. The dynamic test equipment is assumed to be virtually all off-the-shelf equipment such as gyros and accelerometers and very little in the way of component development and qualification will be required.

Operations costs were not estimated at this time but would consist of transportation (to KSC), and ground operations for preparation for STS installation and postflight disposition plus support activities during the flight.

6.1.5 ANNUAL FUNDING REQUIREMENTS. Annual funding requirements by years after go-ahead for development and flight article fabrication were generated by spreading individual cost elements in accordance with the subsequent program schedules discussed in section 6.2 (see Figure 6-2).

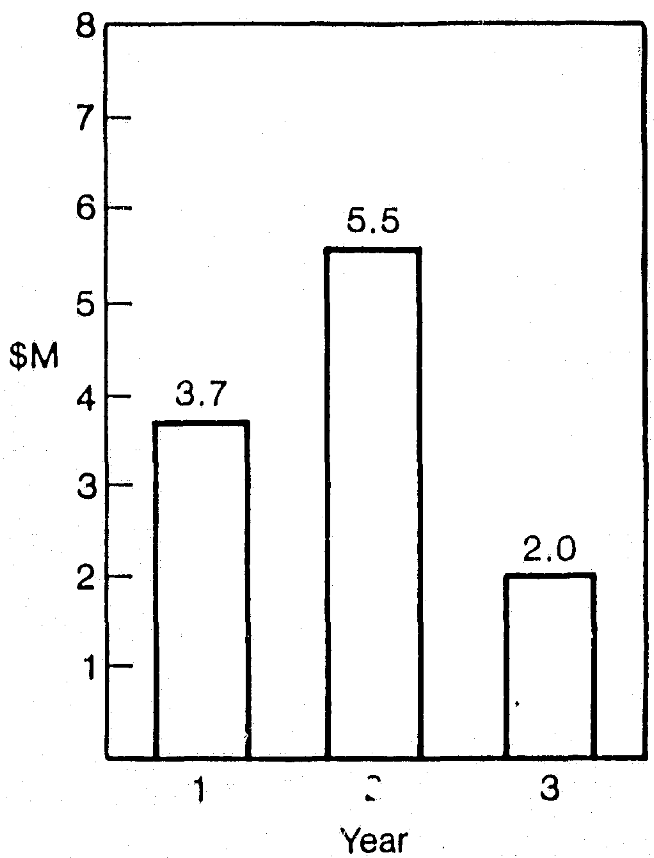

Figure 6-2. Annual Funding Requirements.

6.2 PROGRAM DEVELOPMENT PLAN

Based on the overall program scope of the experiment a summary program development schedule has been established. The schedule (Figure 6-3) represents a nominal development approach keyed to a flight 47 months after go-ahead.

The approach used to develop these master schedules was to first establish the overall program milestones. All major functional task areas were then identified, together with the necessary sequence of major activities and events. These were to include the sequence of functions and tasks required for each of the principal phases: experiment development and test, flight article fabrication, and the operational flight. Once these major milestones and tasks were identified, detailed program milestones, task durations, and other pertinent data were laid out in the master program schedule. They key activities of each functional task area discipline are identified and time-phased relationships to each other and to the external program milestones were identified.

Initial design and analysis and development milestones include a Preliminary Requirement Review (PRR) at eight weeks and a Preliminary Design Review (PDR) at seven months. The Critical Design Review (CDR) follows PDR by eight months. The first tooling is available for the parts fabrication in sixteen months, and the overall experiment fabrication is completed at 30 months. Contractor development system testing, and acceptance testing of the flight hardware is completed in about 34 months. System testing of the SCE is preceded by the normal element, component and subassembly testing in support of the development effort. The SCE is then delivered to LaRC for additional system level testing.

Following NASA testing, the SCE is transported to John F.Kennedy Space Center (KSC) for a two-month period for integration processing and installation into the Space Transportation System (STS). This period is followed by the operational launch, deployment, and test.

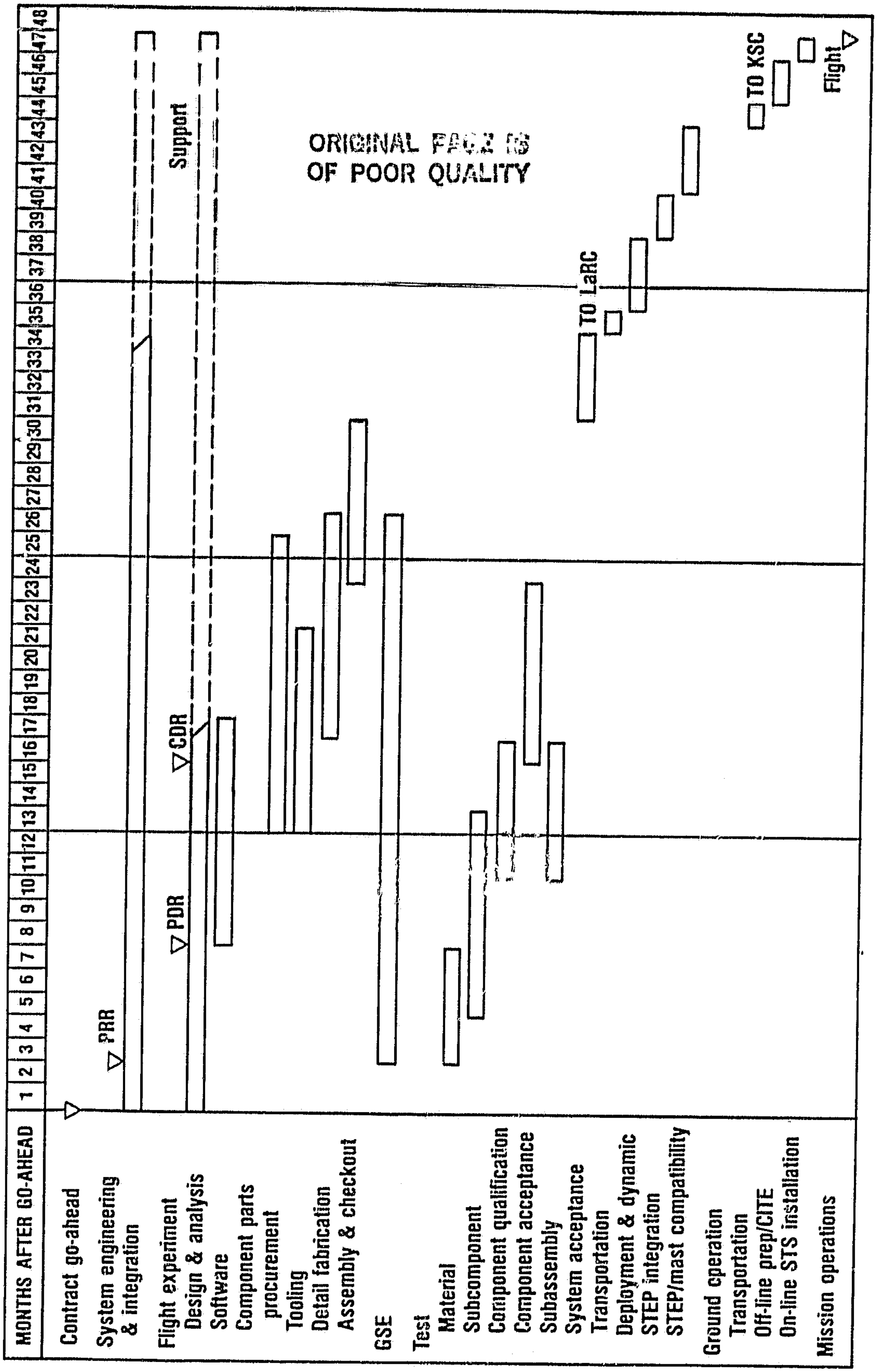

Figure 6-3. Preliminary SCE Program Development Schedule.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

This section presents the major conclusions and recommendations from the SCEDS Part III study effort.

7.1 CONCLUSIONS

a. The essential controls and dynamics community needs for large space structures can be addressed by the basic SCE/MAST configuration from Part II and enhanced configurations for follow-on flights.

b. The SCE/MAST can be integrated on a single structures Technology Experiments Platform (STEP).

c. The experiment objectives can be accomplished without the need for EVA and it is anticipated that further design refinements will eliminate the requirement to use the RMS.

d. Flight of the SCE/MAST is achievable 47 months after program go-ahead.

e. Total SCE/MAST program cost, in 1983, is estimated at $11.2 Million.

7.2 RECOMMENDATIONS

Proceed with SCE/MAST program development and as a minimum immediately commence with:

- Development of a detailed design for the truss
- Development and evaluation of composite joints and fittings
- Evaluation of bus cable and bus format/interconnect options for deployable truss structures.

C-2